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TESTING OF SOLAR PHOTOVOLTAIC ARRAYS FOR UTILIZATION ON MARINE --ETC(U)
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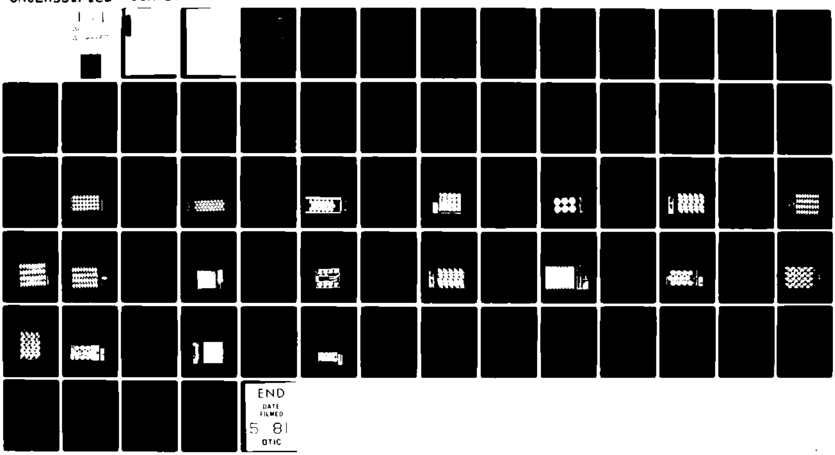

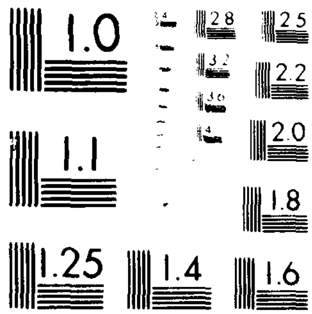

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16. Abstract

In 1978, approximately 400 solar photovoltaic arrays were procured and placed at marine exposure facilities in Groton, Connecticut, and Fort Lauderdale, Florida. The arrays were measured quarterly to ascertain the effects of the marine environment on electrical performance. Concurrently, a screening test for photovoltaic arrays to be used in the marine environment was developed at the Coast Guard R&D Center. Identical panels to those on test at the exposure sites were run through the pressure, immersion, and temperature (PIT) screening test. Based on the marine environment exposure test and the PIT screening test recommendations are made on the constituent materials and construction techniques of solar photovoltaic arrays that are most suited to use in the marine environment.

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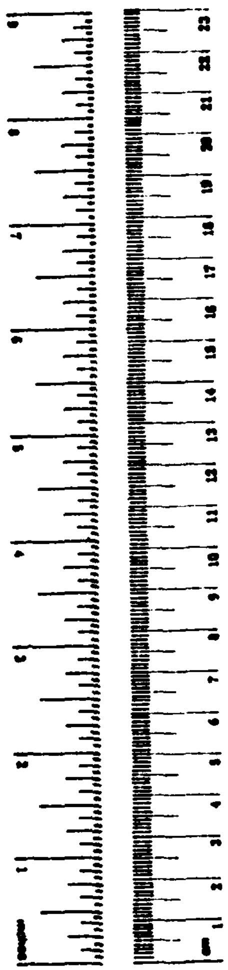
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

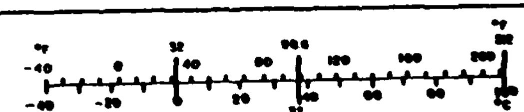


TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.0 INTRODUCTION

Only in the last 20 years has it become practical to convert sunlight directly to electrical energy by the use of the photovoltaic properties of semiconductors. Arrays of these semiconductors have been fabricated to power satellites, and their success and reliability in the space environment is well documented. Their use in the terrestrial environment has not been a universal success.

The severity of the earth environment was initially underestimated by panel manufacturers. Many of the early terrestrial photovoltaic arrays failed because of corrosion and mechanical breakdown under changing temperature, pressure, and humidity. Corrective actions have been taken resulting in the development of more durable photovoltaic arrays. Further, it now appears that solar photovoltaic energy systems may be a cost-effective and reliable means for powering the low-voltage lighted aids to navigation (AN) maintained by the U.S. Coast Guard.[1] The relationship of cost-to-reliability must be established before solar photovoltaics can be accepted into the AN hardware inventory. The problem of reliability is compounded by the rapidly changing technology and the complex structure of photovoltaic devices. The question of reliability in the marine environment must be addressed prior to the deployment of these potentially cost-effective devices.

2.0 BACKGROUND

Early testing at the Coast Guard Research and Development Center was directed at evaluating the interaction of solar photovoltaic energy system components. These tests identified only one highly reliable photovoltaic array. Little knowledge was obtained on the reliability of other photovoltaic arrays, particularly those low-cost arrays that might be cost-effective for AN deployment. The present cost of modern photovoltaic arrays ranges from about nine to twenty-five dollars per peak-watt, and the price can be anticipated to drop to as low as $2 per peak-watt in the near future. Consequently, the reliability of these new photovoltaic arrays needed to be evaluated.

In order to develop the necessary reliability estimates, a program to evaluate both production and prototype photovoltaics in the marine environment was undertaken by the Coast Guard Research and Development Center as part of an on-going Natural Energy Sources Project. This effort was embodied as the Natural Environment Exposure Test (NEET). To assist, two facilities have been established. One, located in the northeast, at Avery Point, Groton, Connecticut, is characteristic of a northern marine climate; the other, located in the south, at CG Station Fort Lauderdale, Dania, Florida, is characteristic of a southern marine climate. At each location mounting stands were constructed in close proximity to the seas to simulate the conditions found on an aid to navigation. Together these exposure sites are representive of the climate under which the Coast Guard deploys aids to navigation.[2]

In 1978, some 400 solar panels from nine manufacturers were procured and placed at these two marine exposure facilities. Ten panels of a particular model were placed at each facility. Within two years of placing the panels on the exposure facility, the majority of the solar manufacturers had ceased marketing the particular models of panels on test. Rather than continuously buy newer models of panels, it was decided that the analysis would be done in terms of materials and construction techniques. The most reliable panel, or panels, were to be identified from the test. This information then could be used to establish a specification for the purchase of future panels.

3.0 ARRAY MATERIALS AND ENCAPSULATION TECHNIQUES

Although solar array manufacturers have been changing models at a rapid rate over the last two years, encapsulation techniques and array materials have been changing at a slower rate. Some model changes have been variations of only a single material in the panel.

In order to analyze the performance of the solar arrays being tested in the marine environment, it was necessary to categorize the encapsulation materials and techniques. There is no generally recognized system of encapsulation classification, so for the purposes of this report, the arrays were separated into the following categories:

Conformal Cover Photovoltaic Array (figure 1) - In this array, the sealant forms both the cover surface of the panel and the pottant between cells. The thick substrate provides the mechanical strength for the array. The cells are adhesively bonded to the substrate and the sealant is poured over the cells to form the covering surface.

Conformal Substrate Photovoltaic Array (figure 2) - The sealant in this array forms the substrate of the panel and the pottant between cells. The cells are bonded to the back surface of the cover of the array and the sealant is poured over the cells to form the substrate of the array. The sealant/substrate is usually covered by a flexible moisture barrier material such as tedlar or aluminum foil. The cover plate of the array provides the mechanical strength of the array.

Film Laminate Photovoltaic Array (figure 3) - In this array, the covering material and substrate are both the same material (i.e., polymer or glass). An adhesive/sealant holds the cover and transparent substrate together and the cells in place. An alternative method is to use an edge gasket and/or frame in addition to an adhesive.

Rigid Lamina Envelope Photovoltaic Array (figure 4) - This panel is identified by a rigid cover plate and a rigid substrate of dissimiliar materials. The cover plate, usually glass or plastic, is fixed to the opaque substrate by the frame. The substrate in this array provides the mechanical strength of the array.

Table 1 lists the constituent materials of the arrays tested at the exposure facilities. Serial numbers were assigned to identify the various models. The encapsulation technique used in each particular model and the materials used to make up the encapsulation system are also listed.

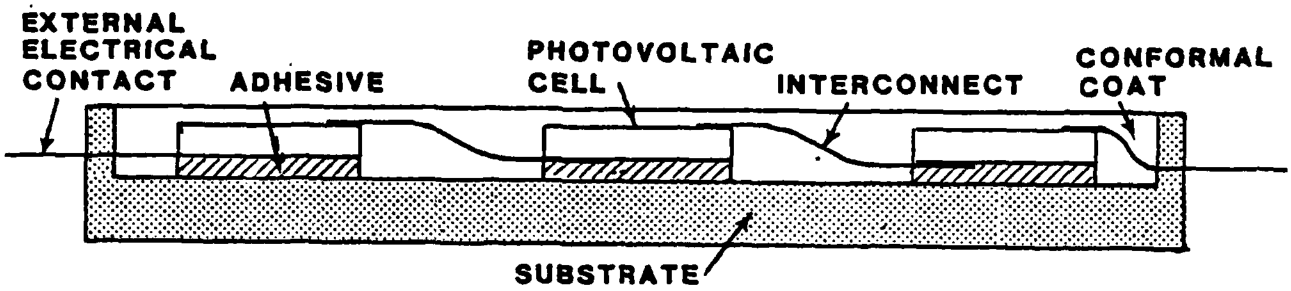


FIGURE 1. CONFORMAL COVER PHOTOVOLTAIC ARRAY

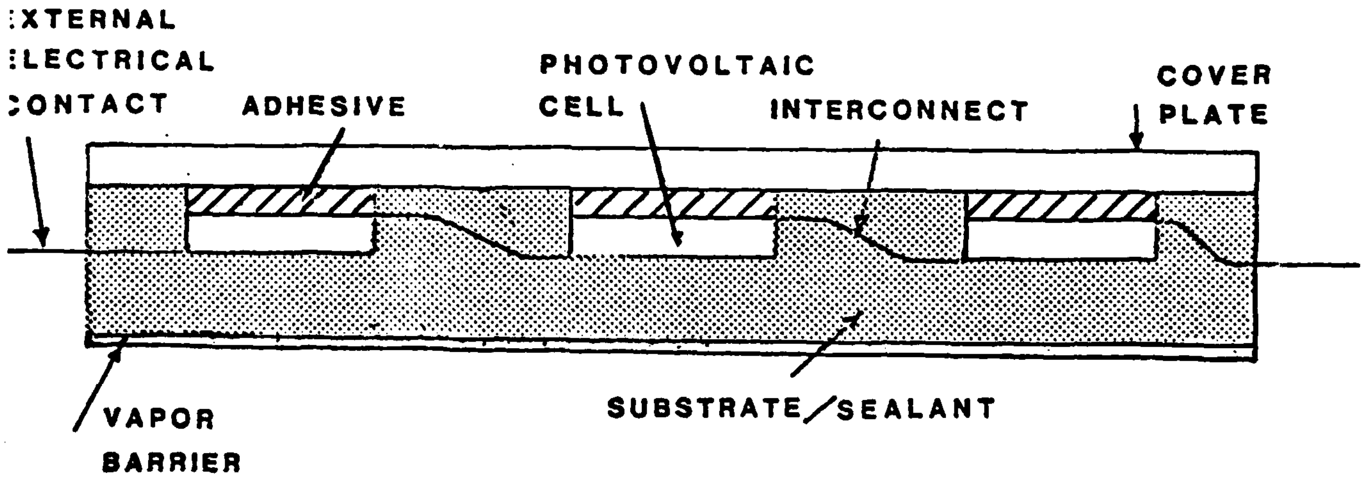


FIGURE 2. CONFORMAL SUBSTRATE PHOTOVOLTAIC ARRAY

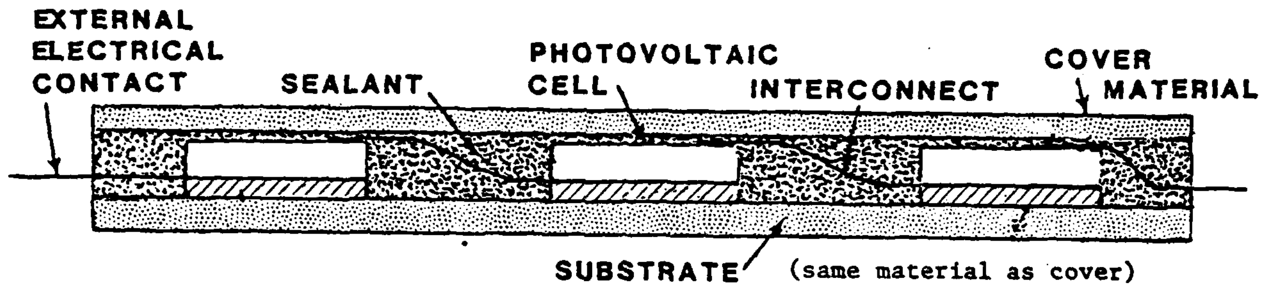


FIGURE 3. FILM LAMINATE PHOTOVOLTAIC ARRAY

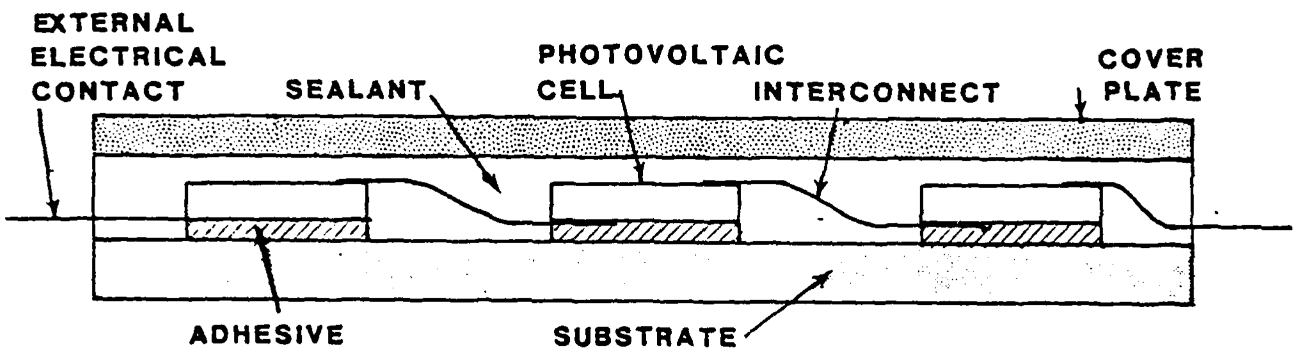


FIGURE 4. RIGID LAMINA ENVELOPE PHOTOVOLTAIC ARRAY

TABLE 1
ARRAY MATERIALS AND CONSTRUCTION TECHNIQUES

PANEL SERIAL NUMBER	ENCAPSULATION TECHNIQUE	COVER	SUBSTRATE	SEALANT/ ADHESIVE/ CELLS	POTTANT	ARRAY INTERCONNECT	TERMINATION	OBSERVATIONS
0500	Rigid lamina envelope	Lexan[R]	Fiberboard	32 ea, 55mm	2-part RTV	Tin-plated copper	Teflon-coated wire pigtails	
1100	Conformal cover	Silicone rubber	Glass-reinforced polyester	36 ea, 90mm	Silicone rubber	Solder-coated copper	Phenolic junction box	
1200	Rigid lamina envelope	Low iron-tempered glass	Aluminum extrusion	18 ea, 55mm	Silicone GE615	Alloy 110, copper	Barrier strip	
1400	Film laminate	Borosilicate glass	Borosilicate glass	6 ea, 55mm	RTV silicone rubber	Expanded copper mesh	Brass standoffs	
1500	Film laminate	Glass-tempered	Glass	6 ea, 55mm	2-part RTV	Tin-plated copper	Teflon-coated wire pigtails	Brass frame
1600	Rigid lamina envelope	Glass, Sunadex	Tedlar on aluminum	20 ea, 75mm, 1/4 cell	Polyvinyl butyrl	Copper	Amp plug	Anodized Aluminum Frame
1700	Rigid lamina envelope	Glass-tempered	Anodized aluminum	36 ea, 55mm, 1/2 cell	2-part RTV	Solder-coated copper	Junction box	
1800	Conformal cover	Silicone rubber	Glass-reinforced polyester	36 ea, 55mm, 1/2 cell	Silicone rubber	Solder-coated copper	Phenolic junction box	
2000	Conformal Substrate	Glass, soda lime	GE615 RTV inside frame	36 ea, 20mmx20mm square	GE615 RTV	Copper	Posts	Corrosion Resistant Aluminum Frame
2100	Film laminate	Glass	Glass	8 ea, 75mm, 1/4 cell	Dow Corning 184 silicone	0.004 tinned copper	Phenolic box	Anodized Aluminum Frame
2200	Rigid lamina envelope	Glass, Sunadex	Tedlar on aluminum	20 ea, 75mm, 1/4 cell	Polyvinyl butyrl	Copper	Amp plug	
2300	Rigid lamina envelope	Glass, tempered	Stainless steel	36 ea, 75mm, 1/2 cell	Dow Corning 2-part liquid silicone	Copper Lamina Kapton	Posts	Stainless steel frame
2400	Conformal Substrate	Pyrex glass	Tedlar	12 ea, 75mm	Polyvinyl butyrl	Solder-coated copper	Posts	Stainless steel frame
2500	Conformal Coat	Tedlar Vapor Barrier	Aluminum	36 ea, 75mm, 1/4 cell	Polyvinyl butyrl	Solder-coated copper	Posts	
2600	Conformal Substrate	Glass, Sunadex	Tedlar	12 ea, 75mm	Polyvinyl butryl	Solder-coated copper	Posts	Stainless steel frame
2700	Conformal Substrate	Glass, soda lime	GE615 RTV	36 ea, 20mmx20mm square	GE615 RTV	Copper	Wire pigtails	Identical to 2000 without frame
2800	Rigid lamina envelope	Pyrex glass	Aluminum foil vapor barrier	12 ea, 75mm	Polyvinyl butyrl	Solder-coated copper	Posts	Stainless steel frame

4.0 MEASUREMENT TECHNIQUES

The goal of the measurement techniques used in this experiment was to provide a means to discriminate among various panels as they react to the marine environment. A substantial portion of the evaluation relied on accurate measurements of the electrical characteristics of the individual solar panels. One technique used to quantify the electrical state of a panel is by an illuminated current versus voltage (I-V) curve. (Curve 1 of figure 5 is a typical I-V curve.) Prior to being placed in the testing sequence, all panels had an illuminated I-V curve taken on the solar simulator at Solar Power Corp in Boston. A second illuminated I-V curve is taken after the panels fail in the marine environment to assist in failure analysis.

While the panels are aging in the exposure stands, it was not practical to take complete I-V data of each panel, but information was needed on the electrical state of each panel. To overcome this problem, a second electrical measurement technique was utilized. Three particular points on the panels I-V curves were recorded: Open circuit voltage (V_{OC}); short circuit current (I_{SC}); and test current (I_t). The test current was measured at a voltage equal to 0.375 volts times the number of cells wired in series in the panel. This test point was chosen because it is near the maximum power point of the panel and near the voltage level a panel would operate in aids to navigation use. Changes in the values of these points were expected to be an indication of electrical failure.

4.1 Test Equipment

A portable battery-operated instrument was constructed to measure in situ the array electrical performance at the three points on the I-V curve. Open-circuit voltage was measured directly across the test array leads. Short-circuit current was obtained by measuring the voltage drop across a 0.1 ohm precision resistor. Test current output was obtained by manually adjusting a variable load across the test array leads to a value equal to 0.375 volts times the number of cells in series in the panel. All test outputs were presented in digital form on a liquid crystal display. Additionally, the output of a pyranometer was continuously displayed. Measurements were made in the following sequence and manually recorded:

a. Insolation on pyranometer
b. Short circuit current test array
c. Open circuit voltage test array
d. Current output at test voltage of array
e. Insolation on pyranometer

The pyranometer was used to monitor changes of insolation during an individual array measurement. If the insolation changed more than 5.0 percent during the measurement of an individual array, the insolation was considered to be too variable and the measurement was repeated. The individual panel measurement took about 10 seconds.

4.2 Temperature and Insolation Correction Procedure

The two parameters that have a notable influence on the electrical performance of a panel are the insolation level and the temperature. The three curves in figure 5 serve to illustrate these effects.

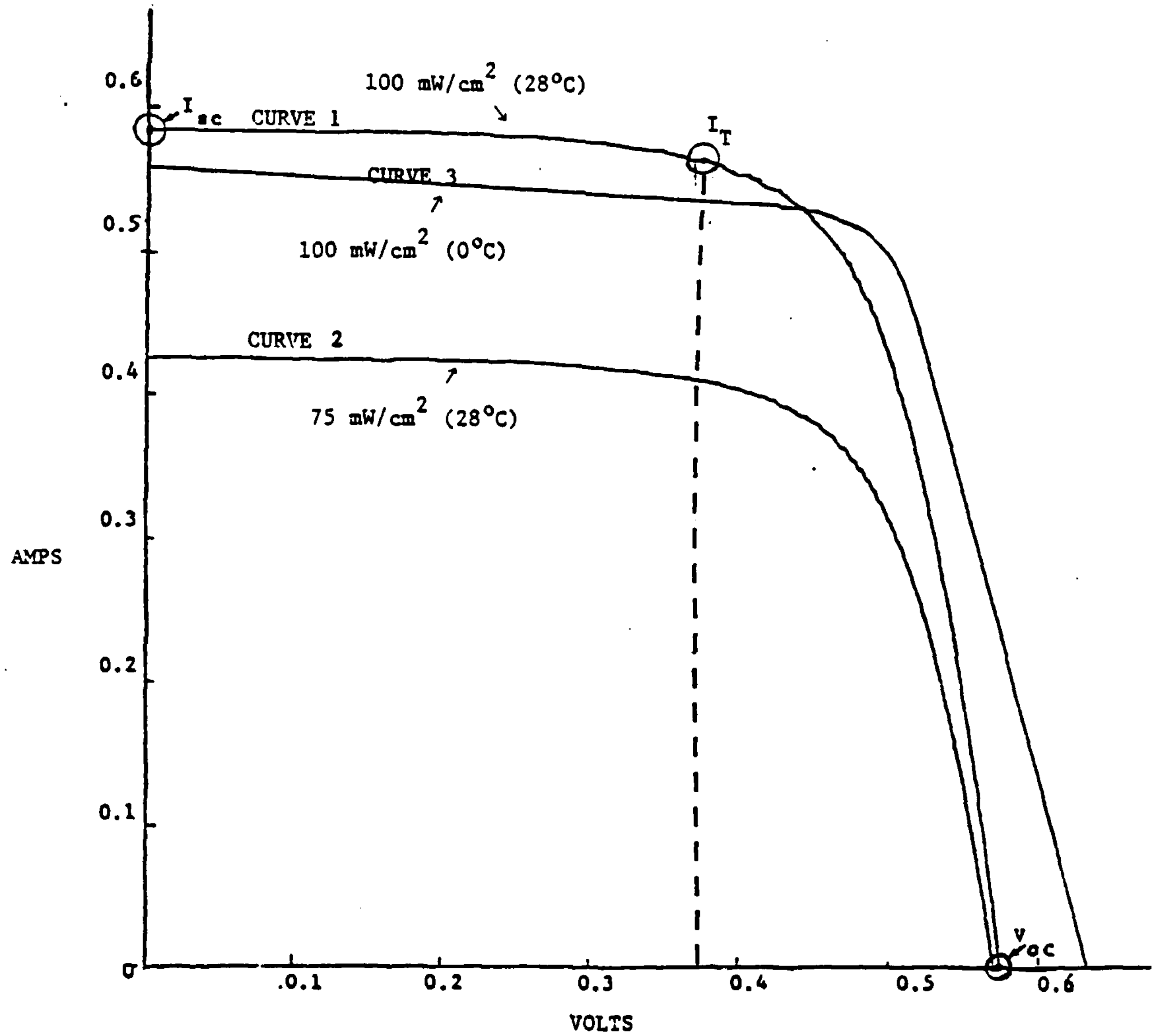


FIGURE 5. TYPICAL I-V CHARACTERISTICS OF SOLAR CELLS

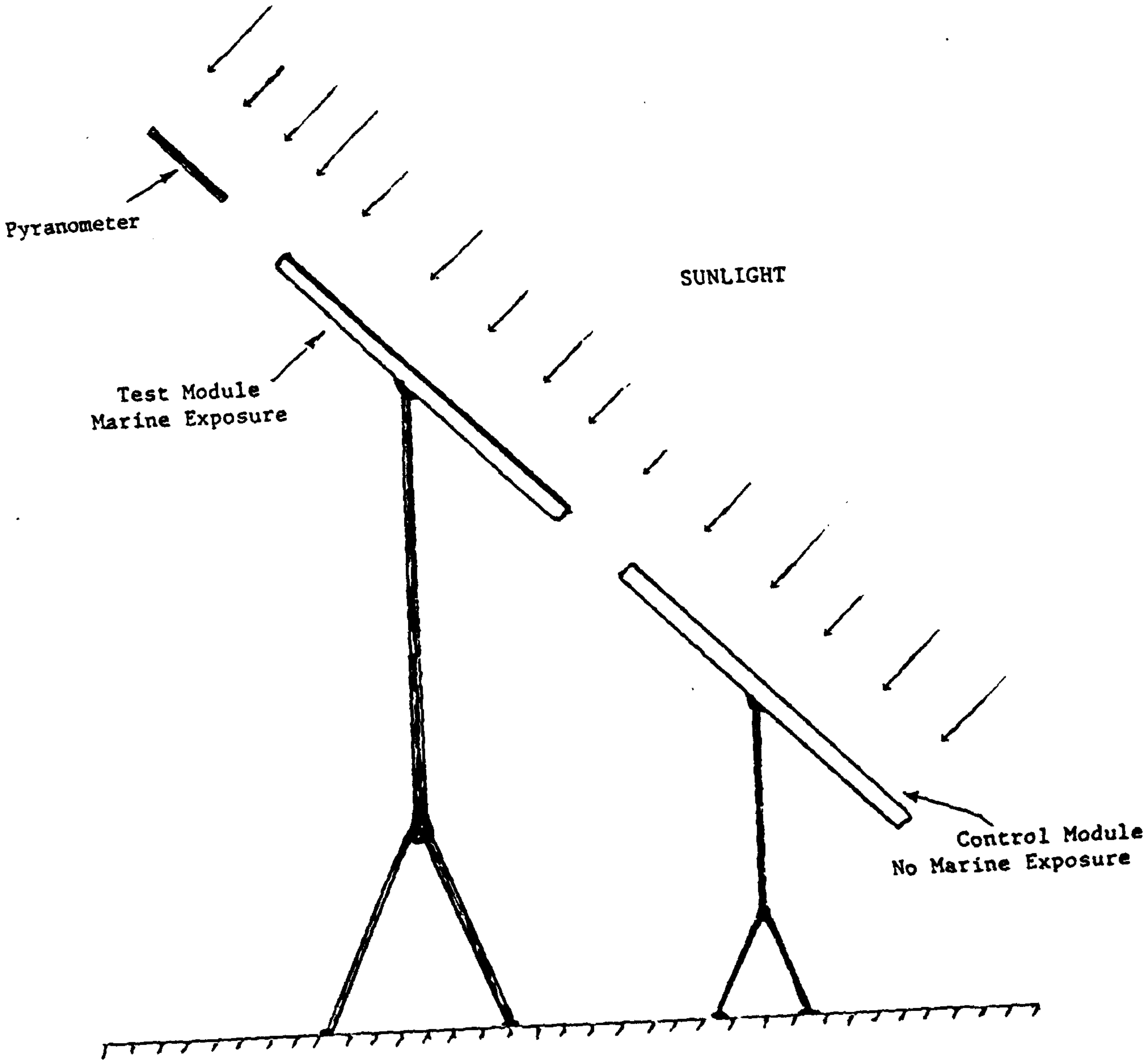


FIGURE 6. OUTDOOR SETUP FOR ARRAY MEASUREMENTS

Curve 1 shows the I-V curve of a solar panel taken at the standard conditions of 100 mW/cm^2 insolation and 28°C. Curve 2 was taken at 75 mW/cm^2 and 28°C. Curve 3 was taken at 100 mW/cm^2 and 0°C. Lower insolation (curve 2) reduces the current output at lower voltages but has almost no effect on open circuit voltage. Lower temperature (curve 3) reduces the current output at lower voltages to a lesser degree but increases the open circuit voltage. At temperatures greater than 28°C, the opposite effects are noted.

To compare readings between outdoor measurements, it is necessary to compensate for insolation and temperature changes. To accomplish this, all test arrays were measured relative to a control module. The control module was identical to the test arrays but it had been kept in a controlled indoor environment on the assumption that no degradation would take place. During quarterly measurements the control module was placed near the test array with the sun at the same angle of incidence (figure 6). It remained at that location for at least an hour in order to allow its temperature to reach the temperature of the test array. With both the control module and the test array operating at the same temperature, any temperature effects were normalized.

The control module was the first and last array tested in each measurement sequence. The ten test arrays were measured between control module readings. Pyranometer readings provided the illumination level for the control module and test array measurements. This was used to correct between test array current measurements and the control module test current.

4.3 Estimated Error Budget

Due to the nature of the field measurements, several potential errors were introduced. The suspected random errors and their maximum estimated effect on test current are listed below.

a. Accumulated dirt and salt[3] - Due to the location of the panels, they were subject to salt spray and bird droppings. Prior to measurement, they were washed to minimize the effects. Estimated Error 2-5%.

b. Determination of effective irradiance via reference cells[3] - Problems included spectral mismatch between modules and reference cell, variation in the field of view between modules and reference cell, optical mismatch between reference cell and module, and large sun/module angle of incidence. Jet Propulsion Laboratory has observed a maximum error of 6%.

c. Determination of test current via control module - Problems include variations in the field of view between control module, pyranometer, and test array. This is essentially the same problem as determination of effective irradiance via reference cells. Estimated Error 6%.

d. Degradation of control module - Control module output varies with time although not exposed to the marine environment. During the quarterly measurements of the control modules on the solar simulator the maximum error noted was 2%.

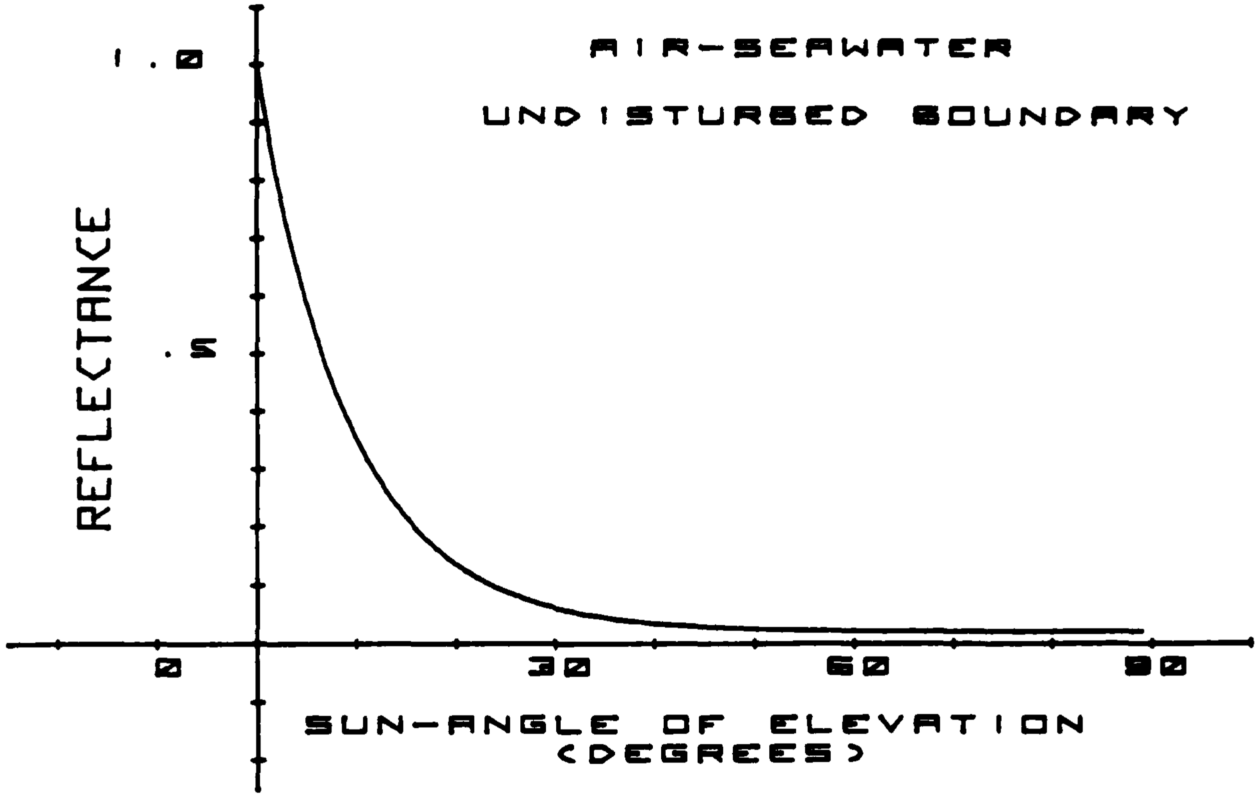


FIGURE 7. REFLECTANCE VERSUS ANGLE OF ELEVATION OF THE SUN FOR AN UNDISTURBED AIR/SEAWATER BOUNDARY

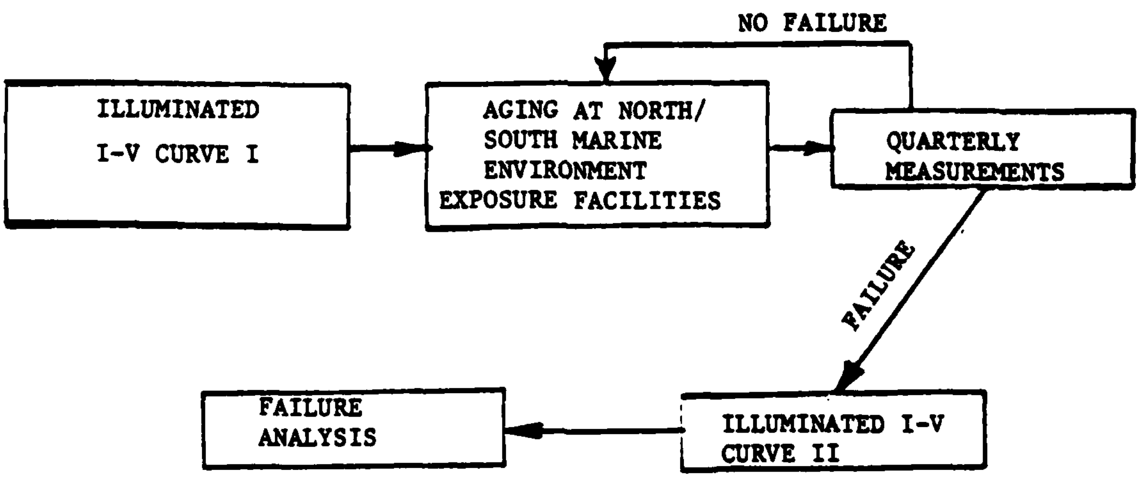


FIGURE 8. EXPOSURE PROCEDURE

Sources of error peculiar to the measurement of photovoltaic panels near bodies of water are variations in the field of view of the pyranometer, control module, and test array due to reflections from the water. Specular reflection of sunlight is one source. The magnitude of specular reflection may be computed from the Fresnel reflection formula. Figure 7 is a plot of reflectance vs angle of elevation of the sun for an undisturbed air-seawater boundary. By taking measurements at high angles of elevation (near noon) the specular reflectance is minimized. Horizontal or near horizontal panels also minimize the amount of incident reflected energy.

Unfortunately, the air-seawater boundary is rarely undisturbed during field measurements. Waves on the surface of the water create multipath and non-specular reflections. These reflections, due to their temporal nature, create random errors that are not well behaved or easily predicted.

4.4 Exposure Procedure

Each panel was subjected to the procedure illustrated in figure 8. The exposure procedure is described as follows:

a. Illuminated I-V Curve I. Prior to exposure of the panels in the marine environment, an illuminated current versus voltage I-V curve was taken to provide a reference I-V with which to measure the effects of exposure. This I-V curve was taken on a solar simulator at Solar Power Corp. in Boston, MA.

b. Exposure. The panels were installed on a structure at either the Northern or Southern Exposure Facility. Each panel is electrically loaded by means of a resistor with a value chosen such that the output voltage of the panel is 0.375 volts per cell. This loads each panel near its maximum power point forcing all panels to operate at a similar point on their I-V curves.

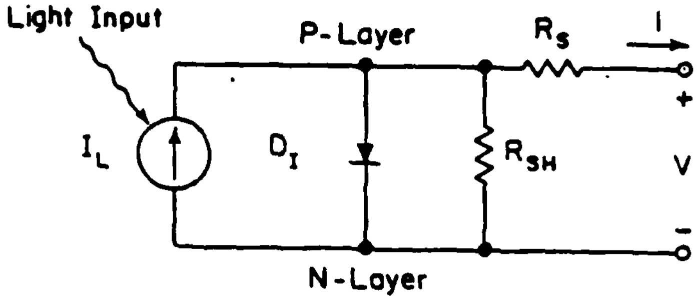
c. Quarterly Measurements. Every three months the electrical characteristics of the panels under exposure are measured in situ to gauge the effect of the marine environment. A panel remains on the test stand if its current output remains high while panels with less than 60% of new current output are removed and returned to the R&D Center.

d. Illuminated I-V Curve II. A panel with low output is taken to the solar simulator at Solar Power Corp. to generate a second current versus voltage curve. The I-V curve confirms the in situ electrical measurements and serves as a diagnostic tool.

e. Failure Analysis. The failure mode of the panel is identified primarily through the second I-V curve and confirmed by disassembly of the panel.

5.0 FAILURE MODES AND ANALYSIS

To aid in the understanding of photovoltaic array failure modes it is convenient to utilize the widely-accepted equivalent electrical circuit representation (figure 9).



Components of the model:
I_L = Light-generated current source
D_I = Ideal diode
R_S = Series resistance
R_{SH} = Shunt resistance

FIGURE 9. SOLAR CELL MODEL

This solar cell model consists of a current source (photon-generated current), an ideal diode, series resistance and shunt resistance. Changes in the values of the model components can be related to degrading processes acting on the array because they have a characteristic effect on the I-V curve of the panel. Listed are some expected changes in the array and the degradation process responsible in the marine environment:

-- Series Resistance: An increase in series resistance may relate to the corrosion or fracture of cells, contacts, connections, or interconnects. The I-V result is illustrated in figure 10a. Neither the open circuit voltage nor the current output at low voltages is affected by a series resistance increase. The maximum power delivered to the load is decreased.

-- Shunt Resistance: Surface-region and pottant conductance changes will result in a shunt resistance decrease. Intrusion of seawater into the interior of the panel is a likely source of decreased shunt resistance. The resulting I-V curve is illustrated in figure 10b. Shunting currents affect the output current at all voltages and decreases open circuit voltage.

-- Ideal Diode: A fundamental change in the cell-junction characteristic will result in diode losses. The I-V curve result is illustrated in figure 10c. This loss is not expected to be significant in the marine environment as it is related to quality control errors in manufacturing.

-- Light-Generated Current: Optical losses due to delamination or discoloration of the panel cover plate will reduce the light-generated current. The I-V curve result is illustrated in figure 10a. Optical losses have the same I-V effect as reduced illumination. The open circuit voltage, is not affected but current output and maximum power output are reduced.

It should be noted that the three measurement points selected for outdoor measurement (figure 5) should be able to detect and distinguish between the expected degrading processes. This detection will be limited, however, as I-V curves of real arrays usually do not show as distinct a separation of effects as those illustrated in figure 10.

A more complete listing of possible degrading processes relating to optical loss, series resistance increases, and shunting losses is provided in figures 11-13, respectively.[4]

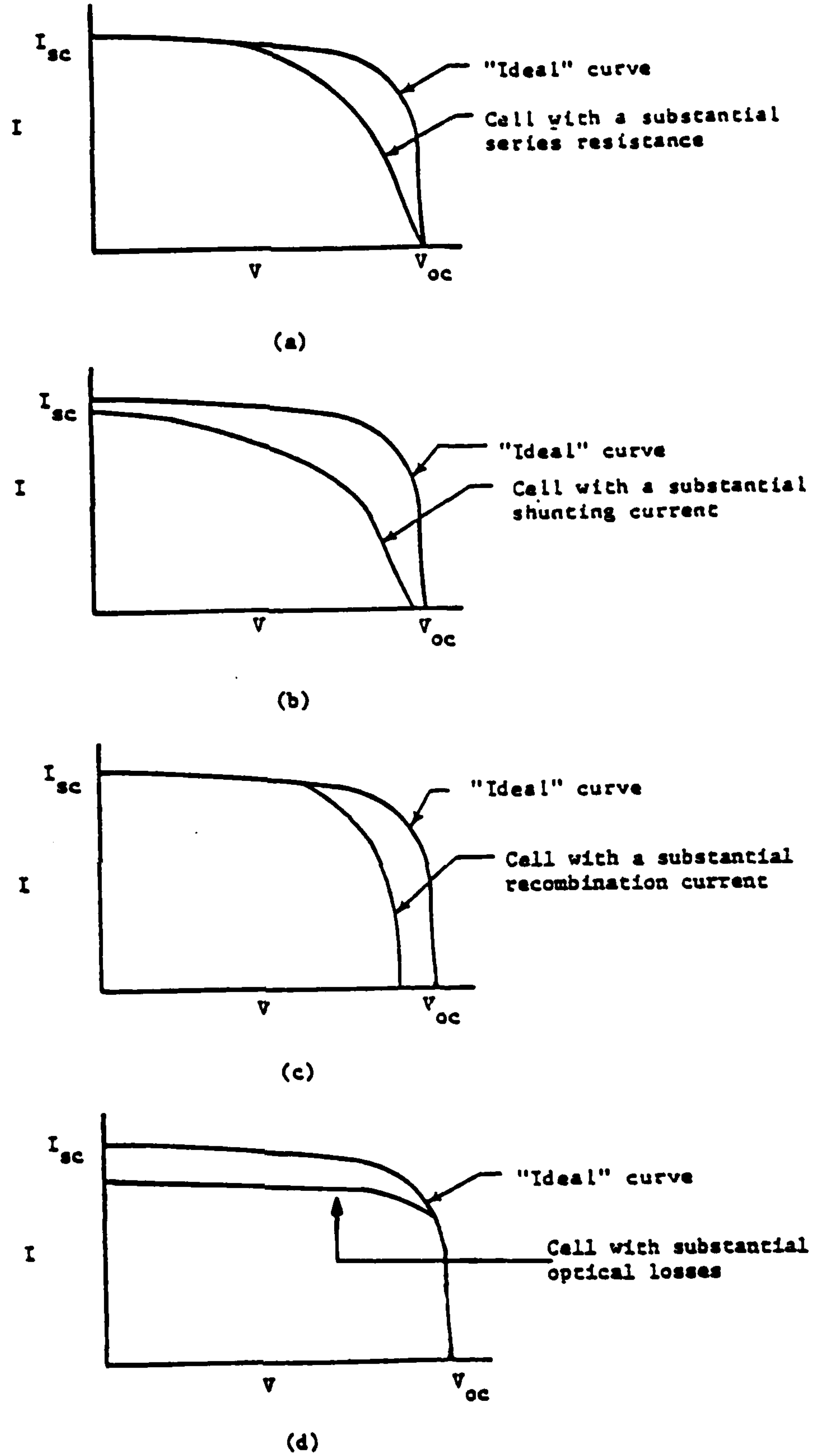


FIGURE 10. SOME RELATIONSHIPS BETWEEN CELL PARAMETERS AND I-V CURVES

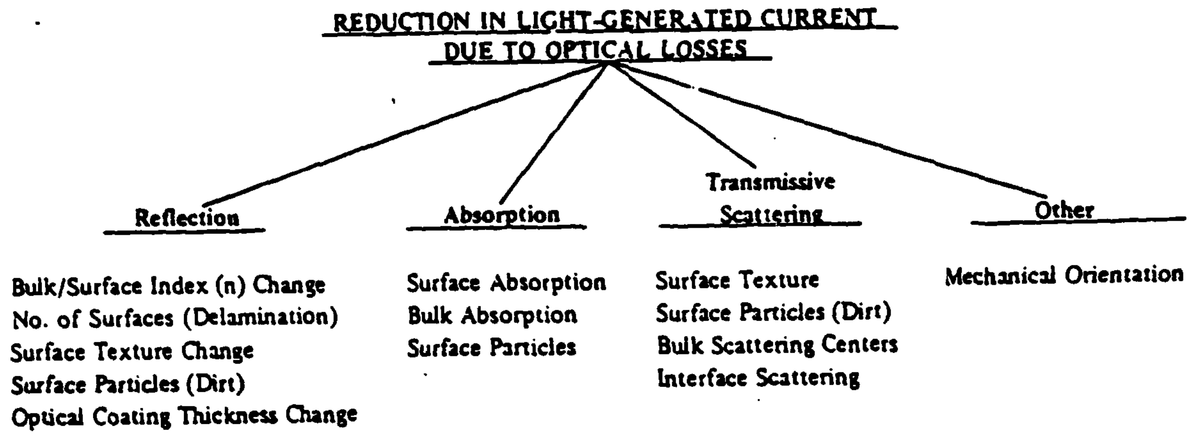


FIGURE 11. BREAKDOWN OF DEGRADATION FACTORS CONTRIBUTING TO OPTICAL LOSSES WHICH CAUSE A DECREASE IN THE LIGHT-GENERATED CURRENT

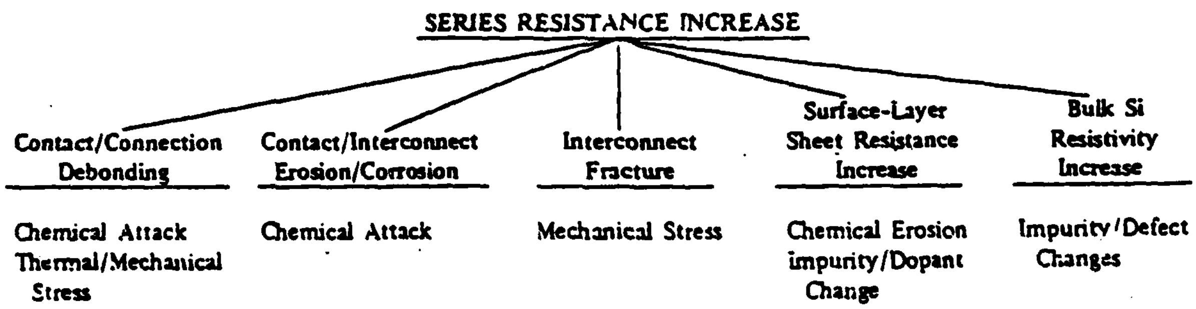


FIGURE 12. DEGRADATION CHANGES MANIFEST AS SERIES RESISTANCE INCREASES

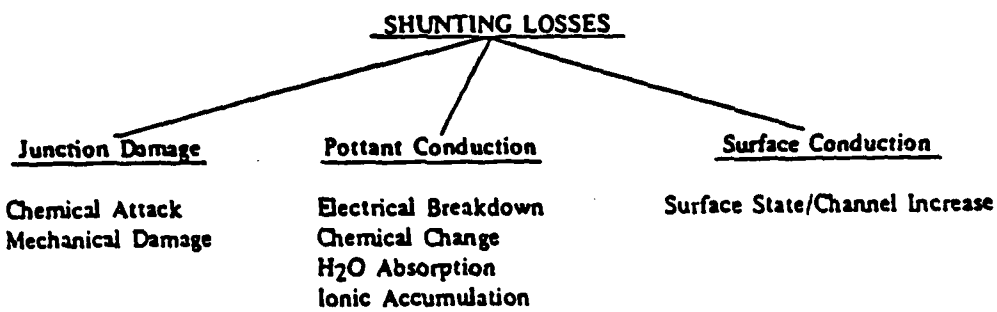


FIGURE 13. DEGRADATION FACTORS CONTRIBUTING TO LOSSES BY SHUNT RESISTANCE DECREASES

6.0 MARINE ENVIRONMENT DATA ANALYSIS

The data collected during the outdoor quarterly measurements is the basis for comparison between solar photovoltaic arrays. Of the three data points collected for each panel, (i.e., V_{OC}, I_{SC}, and I_t) only the test current will be analyzed in detail. This test current point is used for two reasons:

a. A change in the value of the test current is associated with all degradative processes.

b. The proximity of the test current to the maximum power point and the projected system operating point will give a basis for predicted behavior on operational systems.

Changes in the open circuit voltage and the short circuit will be used as indicators of particular failure modes.

6.1 Degradation and Failure Data

Table 2 lists a summary of the panel performance data for both exposure sites as of 1 November 1980. Included is the test quantity, the number of months of exposure, and the number of panels within a model type that have exhibited undesirable behavior.

The totals for undesirable behavior are further broken down in table 3. The first three columns of table 3 list the number of panels for each model type that are exhibiting behavior that is not acceptable for use on marine aids to navigation. The undesirable behavior resulting from marine environmental exposure is broken down into three categories:

Electrical Failure - A test current output of 60% or less than the new test current output.

Electrical Degradation - A test current output greater than 60% but less than 80% of the new test current output.

Visual Degradation - Detrimental changes which are visible to the eye but have not caused any electrical degradation to date. The visual degradation is expected to result in near-term electrical failures/degradation.

Table 3 lists two additional categories of detrimental change:

Non-Environmental Degradation - Changes in the panels that are not due to the marine environment. The most common examples are cracks in the cover plates from mounting problems and damage from vandalism.

Inconsequential Visual Degradation - Visible changes in the panel that are not expected to detrimentally affect the output of the panel in the short term.

TABLE 2

SUMMARY OF PANEL PERFORMANCE DATA FROM THE NORTHERN AND SOUTHERN EXPOSURE SITES

PANEL SERIAL NUMBER	0500	1100	1200	1400	1500	1600	1700	1800	2000	2100	2200	2300	2400	2500	2600	2700	2800	TOTALS
GROTON, CT																		
Test Quantity	10	10	10	10	10	10	10	10	10	10	10	7 (1)(3)	10	10	10	9 (2)	10	166
Exposure (mths)	27	24	24	24	21	21	21	21	21	17	17	17	17	17	15	15	15	
Total Number of Panels Exhibiting Undesirable Behavior (4)	4	9	0	0	0	0	6	1	1	1	1	0	3	3	3	1	10	34
FORT LAUDERDALE, FL																		
Test Quantity	10	10	10	10	10	10	10	10	10	10	10	9 (3)	10	10	10	10	10	169
Exposure (mths)	27	24	24	24	21	21	21	21	21	17	17	17	17	17	15	15	15	
Total Number of Panels Exhibiting Undesirable Behavior (4)	3	7	0	0	1	0	7	4	0	2	0	0	4	0	2	0	10	27

(1) Two modules stolen from stand
(2) One module destroyed in mounting
(3) Only nine modules initially deployed
(4) Sum of electrical failures, electrical degradation, and visual degradations from table 3

TABLE 3

SUMMARY OF UNDESIRABLE BEHAVIOR OF SOLAR PHOTOVOLTAIC PANELS EXPOSED TO THE MARINE ENVIRONMENT

	ELECTRICAL FAILURE(1)		ELECTRICAL DEGRADATION(2)		VISUAL DEGRADATION(3)		TOTAL (ENVIRONMENTALLY INDUCED)	COMMENTS	NON-ENVIRONMENTAL DEGRADATION (4)		INCONSEQUENTIAL VISUAL DEGRADATION (5)	
	NORTH	SOUTH	NORTH	SOUTH	NORTH	SOUTH			NORTH	SOUTH	NORTH	SOUTH
0500	3	1	1	2	0	0	7	Poor sealing techniques				
1100	5	4	4	3	0	0	16	Multiple types of failures				
1200	0	0	0	0	0	0	0					
1400	0	0	0	0	0	0	0	Cover plates cracked during mounting; no panel failures	4	1		
1500	0	1	0	0	0	0	1	Poor sealing at terminals				
1600	0	0	0	0	0	0	0					
1700	0	0	0	0	6	7	13	Pottant burning				
1800	1	2	0	2	0	0	5	Intermittent interconnects, cracked cells				
2000	1	0	0	0	0	0	1	Cracked frame			3	2
2100	0	0	1	2	0	0	3	Pottant discoloration			0	8
2200	1	0	0	0	0	0	1	Poor sealing techniques				
2300	0	0	0	0	0	0	0	Pottant discoloration			6	4
2400	0	0	0	0	3	4	7	Grid corrosion				
2500	2	0	1	0	0	0	3	Pottant breakdown			7	10
2600	0	0	0	0	3	2	5	Grid corrosion			7	0
2700	1	0	0	0	0	0	1	Cover plate cracked during mounting; panel subsequently failed	1	0	6	0
2800	0	0	0	0	10	10	20	Pottant breakdown, vapor barrier delamination				

(1)Failure = 60% or less test current output

(2)Degradation = less than 80% but greater than 60% test current output

(3)Degradative processes that are visible to the eye but have not caused electrical degradation

(4)Visual changes not attributable to environment

(5)Visual changes in the panel which are not expected to detrimentally affect the panel in the short term

Figure 14 is a bar graph presentation of this data grouped by generic panel type.

The comments section lists the general reason for listings in the table.

6.2 Reliability and Failure Analysis

The test current data is analyzed as "% of new current output." This value is the ratio of a test current measured at the exposure site to the initial current output measured on a commercial flash solar simulator. The mean value and the variance of "% of new current output" for each panel type were calculated.

To plot the data, a quantity representing the mean value minus two standard deviations of the "% new current output" was formed. Assuming the panel's test currents are normally distributed about the mean, this quantity represents a level above which 97.5% of the panels were operating at the time of measurement. This is a convenient method to quantify reliability. A panel is penalized if the mean "% of new current output" is low or the variability is high. For example, 10 panels operating at 90% after exposure would have an average output of 90%, a standard deviation of 0% and would plot as 90%. In contrast, another 10 panels, nine operating at 100% and one failed at 0%, would give an average of 90% but a standard deviation of 32% and would plot as 26%. This method has the drawback that measurement errors could increase the variability. For this reason, this plotting method should only be used to identify overall trends of performance.

Figure 15 through 31 contain data and comments on panels that have at least nine samples at each exposure site. Included on the data sheet is a picture of the front of the panel and the panel terminals. Also included on the data sheet is a plot of the panels' "% new current output" mean value minus two standard deviations. The curve labeled "south" represents the output in the southern marine climate and "north" represents the output in the northern marine climate.

The photographs of each panel show their general configuration. Attached at the right is a photograph of the termination technique for each panel.

The panel comments page is a discussion of relevant information concerning the construction of the panel and its behavior in the marine environment. Pictures and I-V curves are also included to illustrate panel degradation or failure modes.

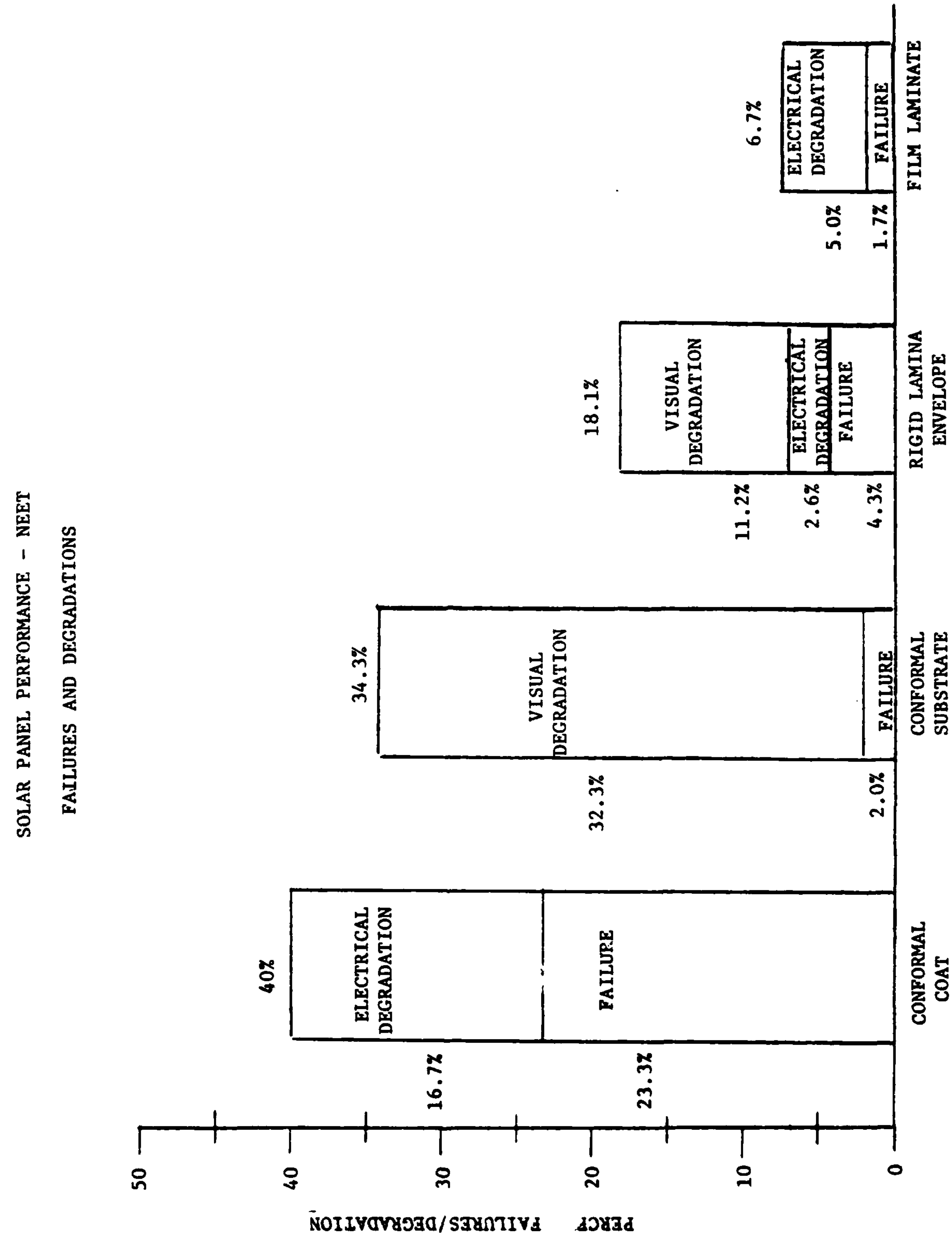
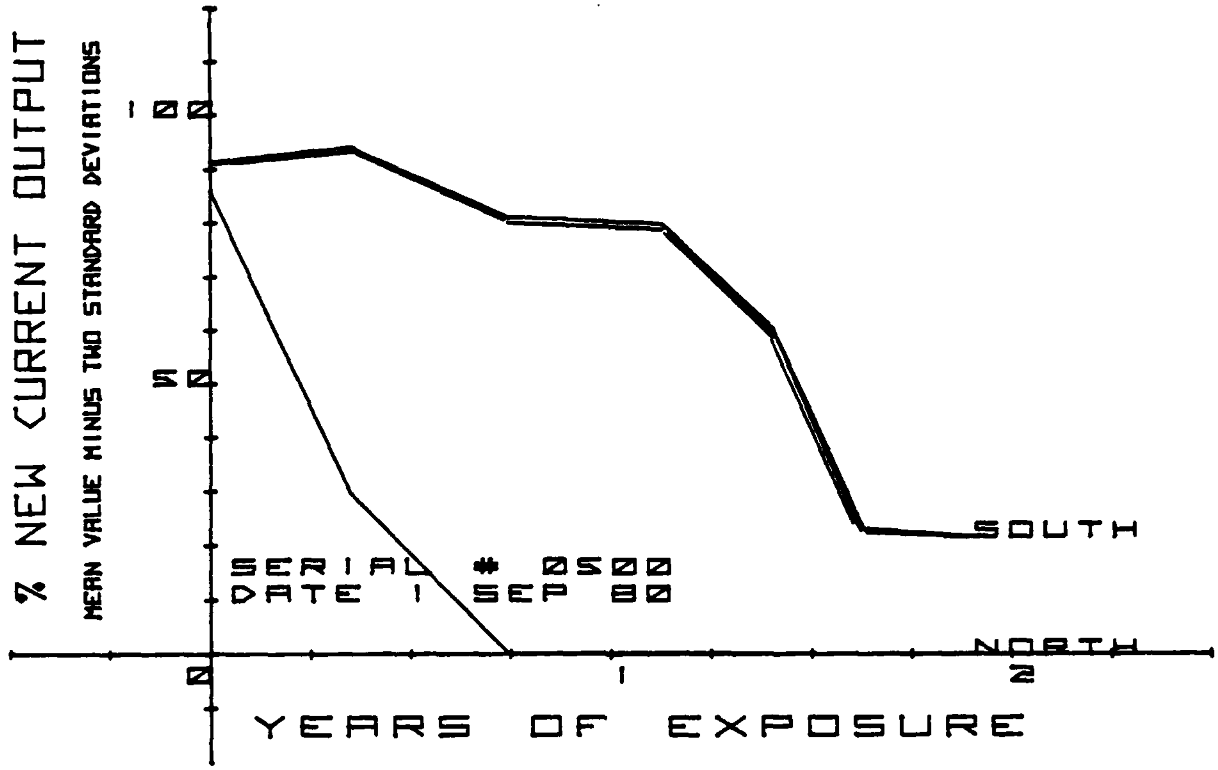


FIGURE 14. SOLAR PANEL PERFORMANCE (NEET)



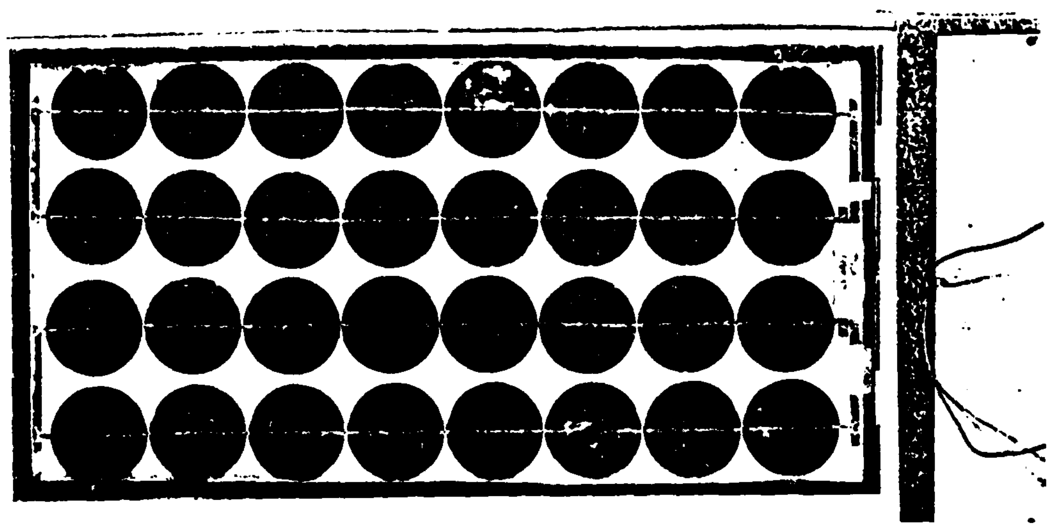


FIGURE 15. 0500 SERIES DATA SHEET

0500 SERIES PANEL - COMMENTS

This panel is of rigid lamina envelope construction with a lexan cover and a fiberboard substrate. The sealant is a 2-part RTV silicone rubber. A black tape gasket seals the edges. The cell interconnects are tin-plate copper and termination is with two pigtails of Teflon-coated wire. The lexan cover is not bonded to the substrate leaving an air gap in the interior of the panel.

Seven panels of this construction have failed to date due to poor sealing techniques. Failed panels are usually filled with seawater. A particularly weak point is where the Teflon-coated wire leads through the gasket of the array encapsulant. Excessive corrosion is evident on the internal side of the lead through. The source of the corrosion is believed to be seawater which is entering either inside of the Teflon-coated wire or just outside of the wire where the Teflon fails to bond completely to the gasket.

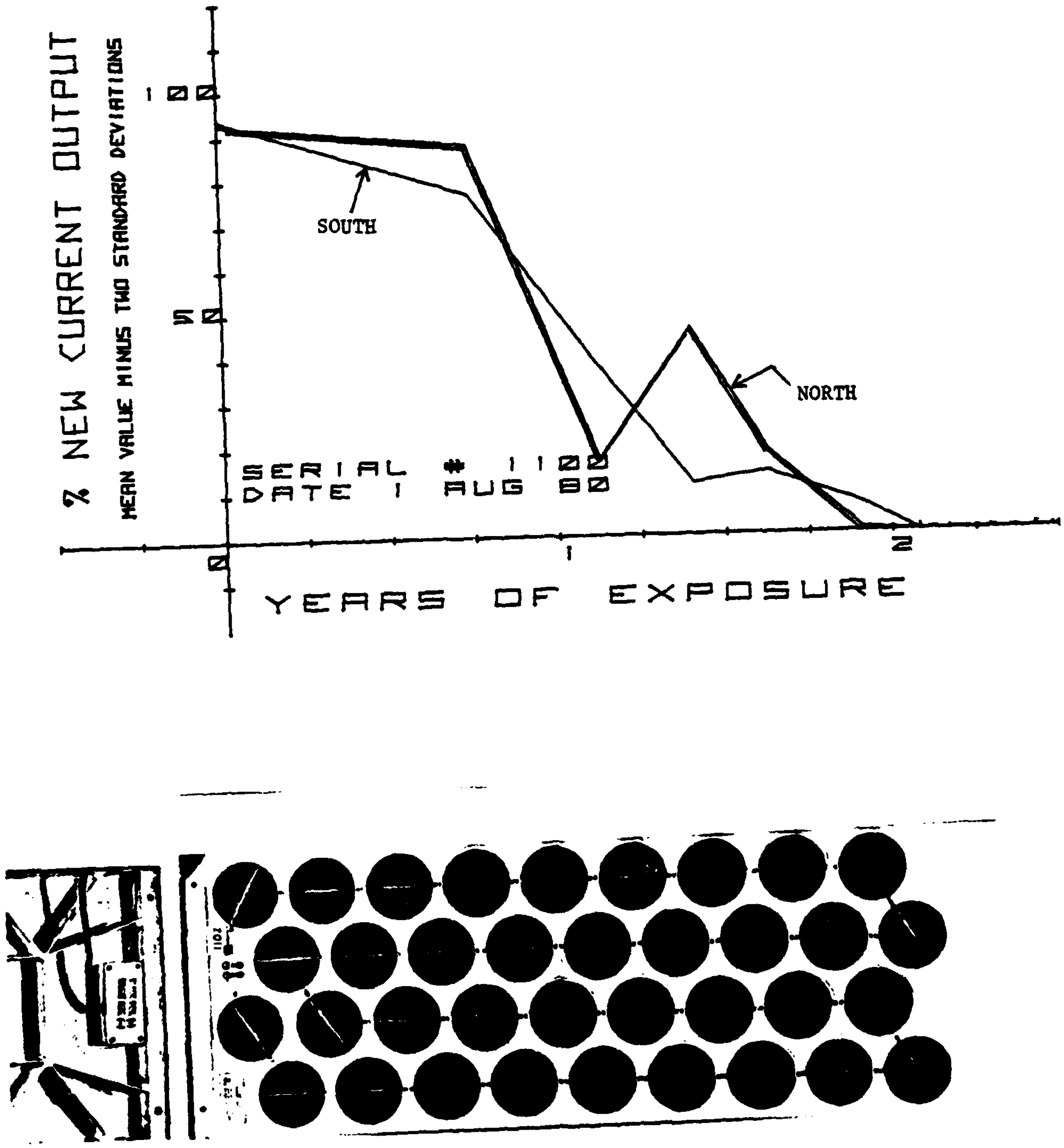
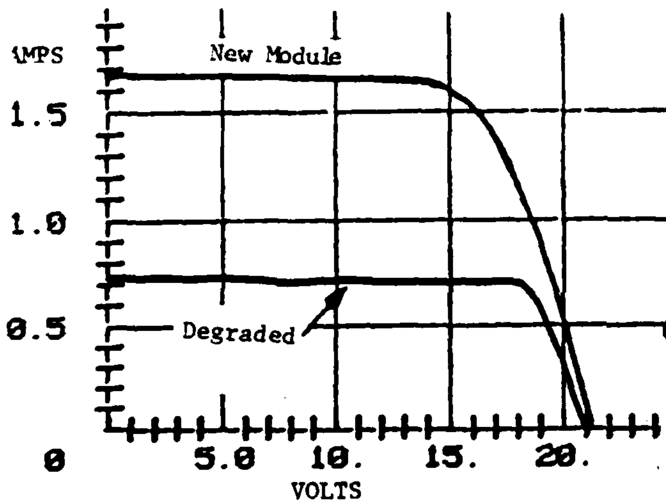


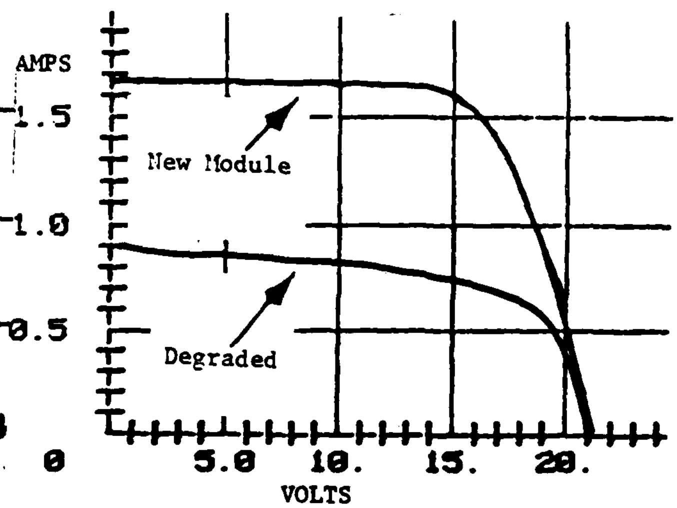
FIGURE 16. 1100 SERIES DATA SHEET

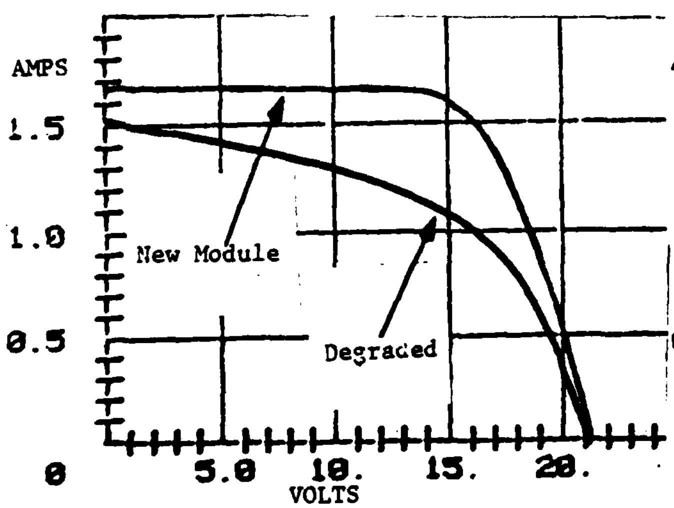
1100 SERIES PANEL - COMMENTS

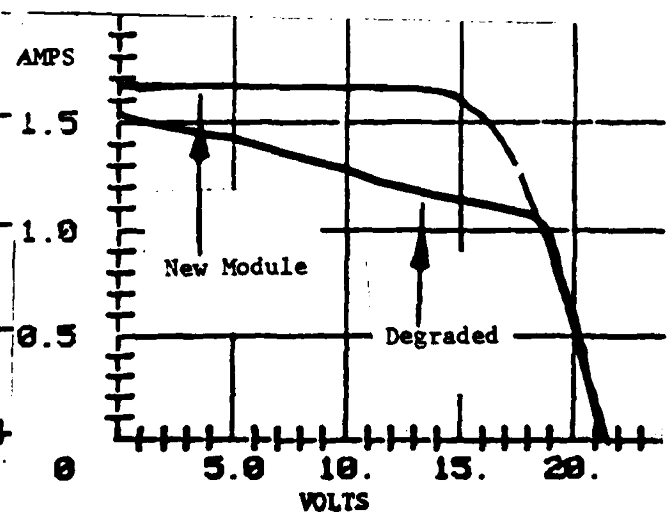
This panel is a conformally coated array with a molded glass reinforced polyester substrate. The conformal coat is RTV silicon rubber. The array has large 90mm cells with tin-plated copper interconnects. The terminals are located inside a junction box which is bonded to the back of the array. This termination technique requires no modification for use in the marine environment.

Sixteen panels of this construction have failed. Attached are I-V curves from electrically degraded 1100 Series panels. The top two I-V curves appear to indicate optically degraded panels and bottom two appear to indicate increased series resistance. Failure analysis revealed that the increased series resistance is due to corrosion of interconnects from water intrusion. Failure analysis has not been able to identify the cause of the apparent optical degradation.









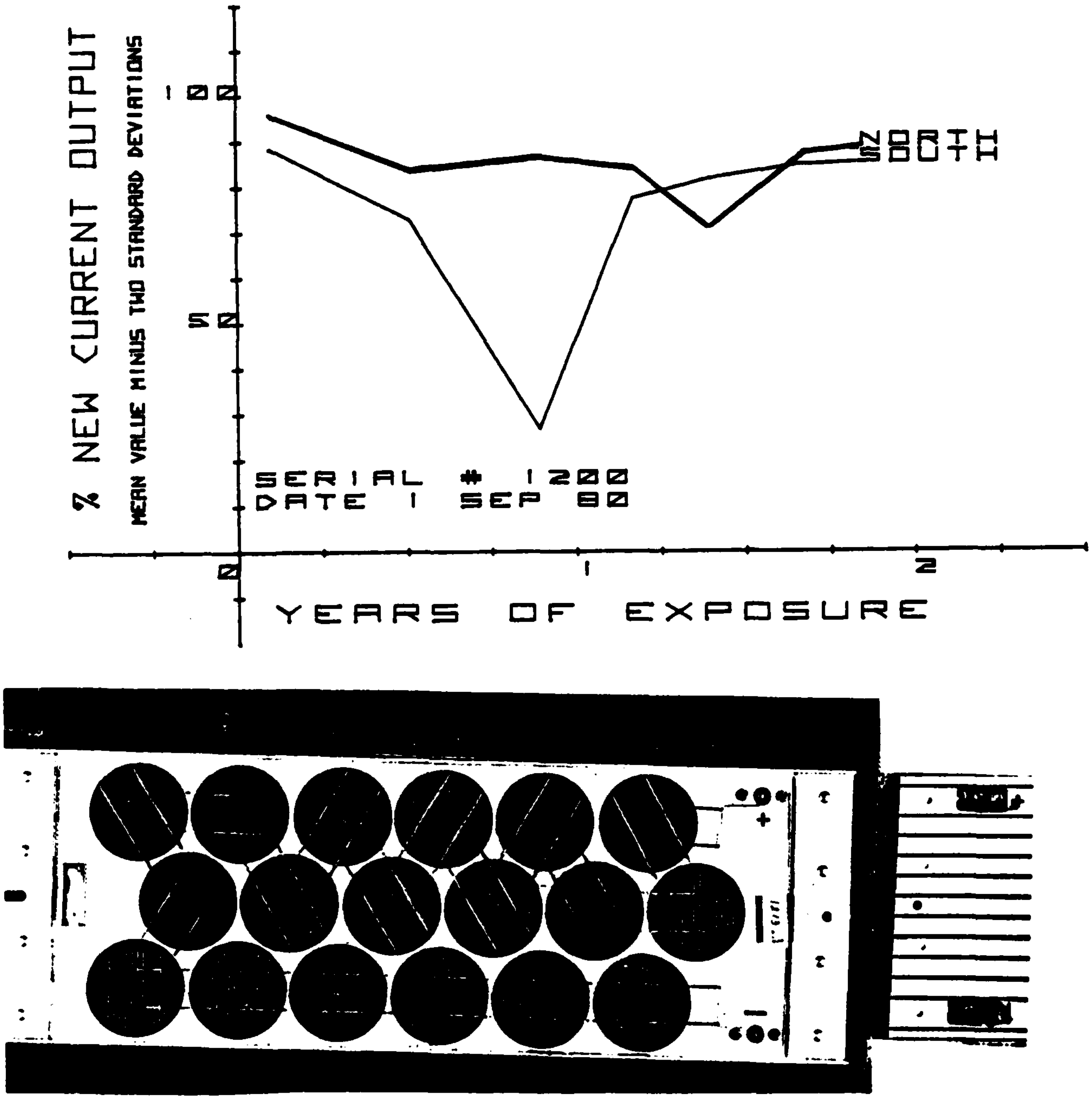
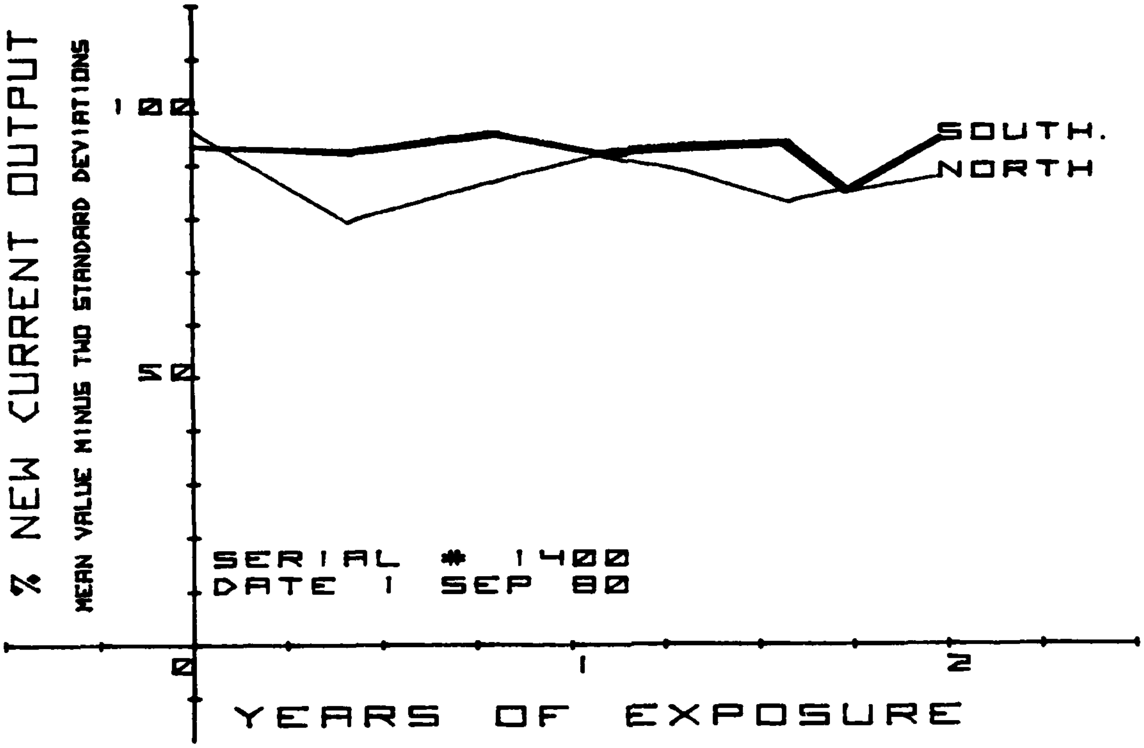


FIGURE 17. 1200 SERIES DATA SHEET

1200 SERIES PANEL - COMMENTS

This panel is of rigid lamina envelope construction with a low iron tempered glass cover and an extruded aluminum substrate. The sealant is GE 615 silicone rubber. The 55mm cells have interconnects which are made of Alloy 110 Copper. As received, the screw terminals on the back of the array were not protected for the marine environment and had to be specially sealed at the Coast Guard Research and Development Center. The substrate provides good mechanical strength to the array, is easy to handle, and should act as a good heat radiator.

These panels have shown no electrical degradation and visually show no signs of the marine exposure. The drop in the current output at nine months was probably due to measurement error.



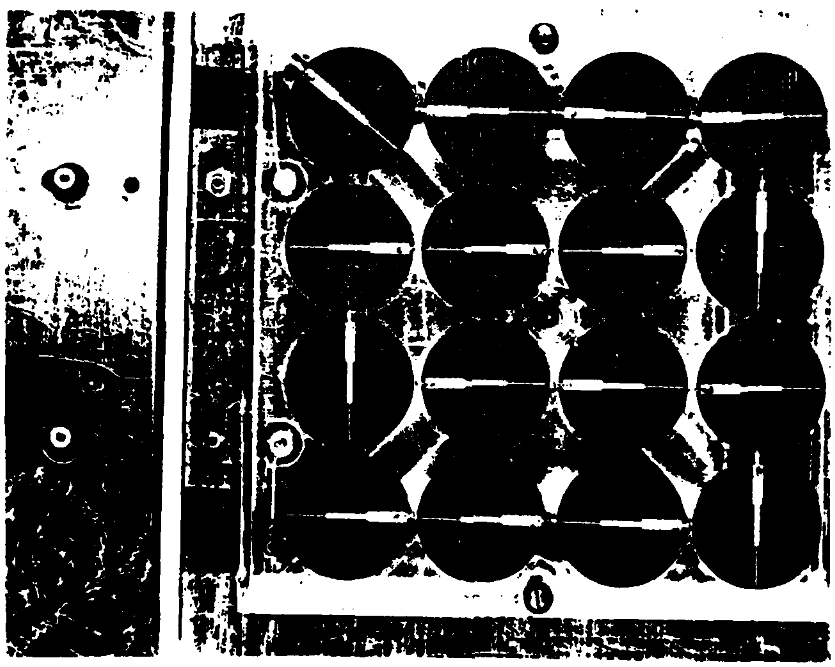


FIGURE 18. 1400 SERIES DATA SHEET

1400 SERIES PANEL - COMMENTS

This is film laminate panel with borosilicate glass on both the cover and the substrate. The sealant is RTV silicone rubber. The panel has expanded copper mesh interconnects and brass standoffs for terminals. The arrays as received, were bolted to a stainless steel plate. In the handling and mounting of the arrays, the glass encapsulant was cracked in many of the panels. The terminals which feed through the glass were intended to be used as circuit board standoffs. They were unacceptable for the marine envionment and were removed. A wire was soldered to the screw that supported the standoff. The terminals were then sealed.

None of these arrays have demonstrated any electrical degradation in spite of the cracked cover plates. This speaks well for the sealant material.

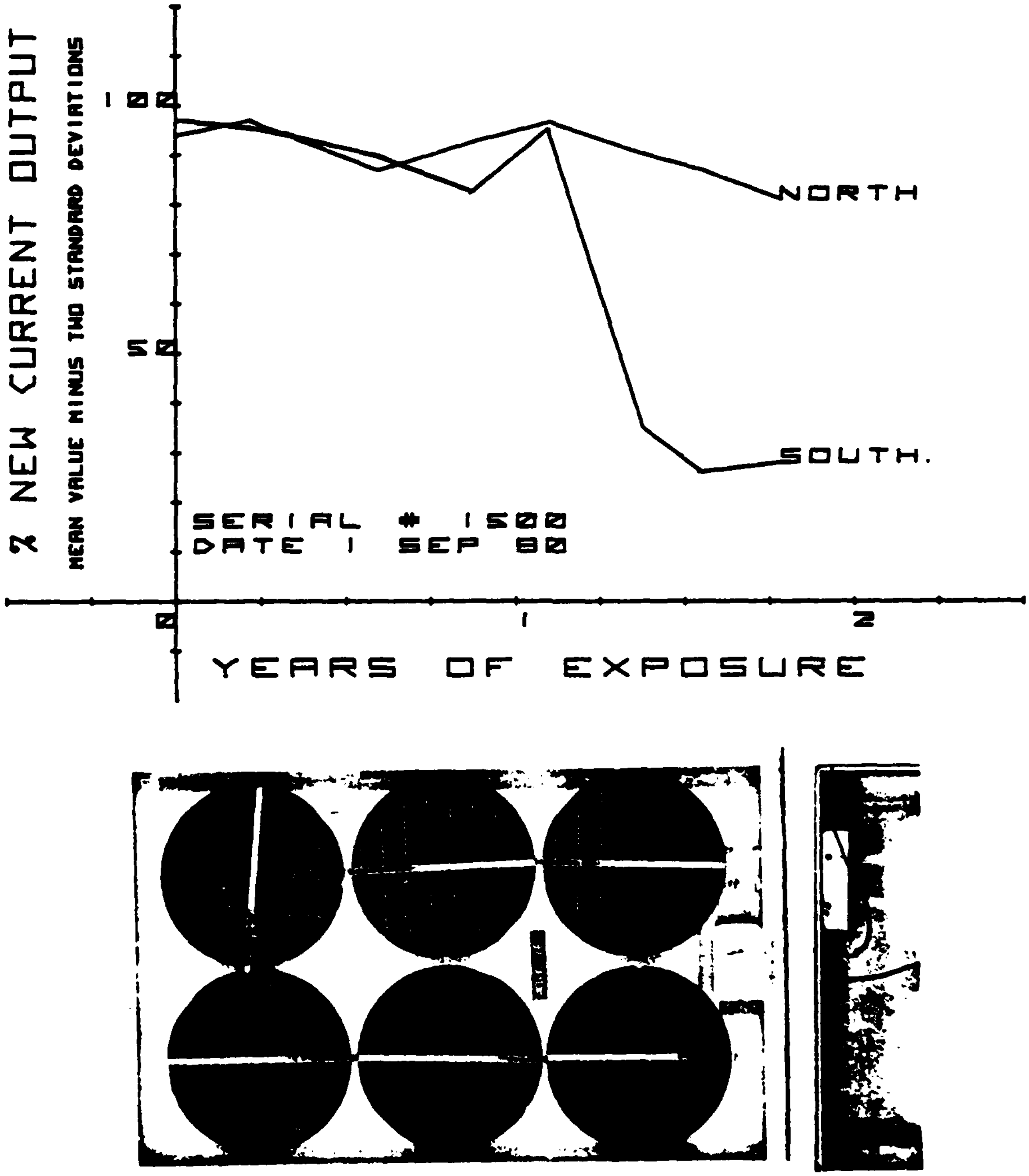


FIGURE 19. 1500 SERIES DATA SHEET

1500 SERIES PANEL - COMMENTS

This panel is of film laminate construction with a tempered glass cover and an opaque glass subtrate. The array has a brass frame and is sealed by RTV silicone rubber. It has 55mm cells and is terminated by two Teflon coated pigtail wires.

One panel has failed electrically. Salt water entering the panel at the point of termination similar to the 0500 series was the cause of failure.

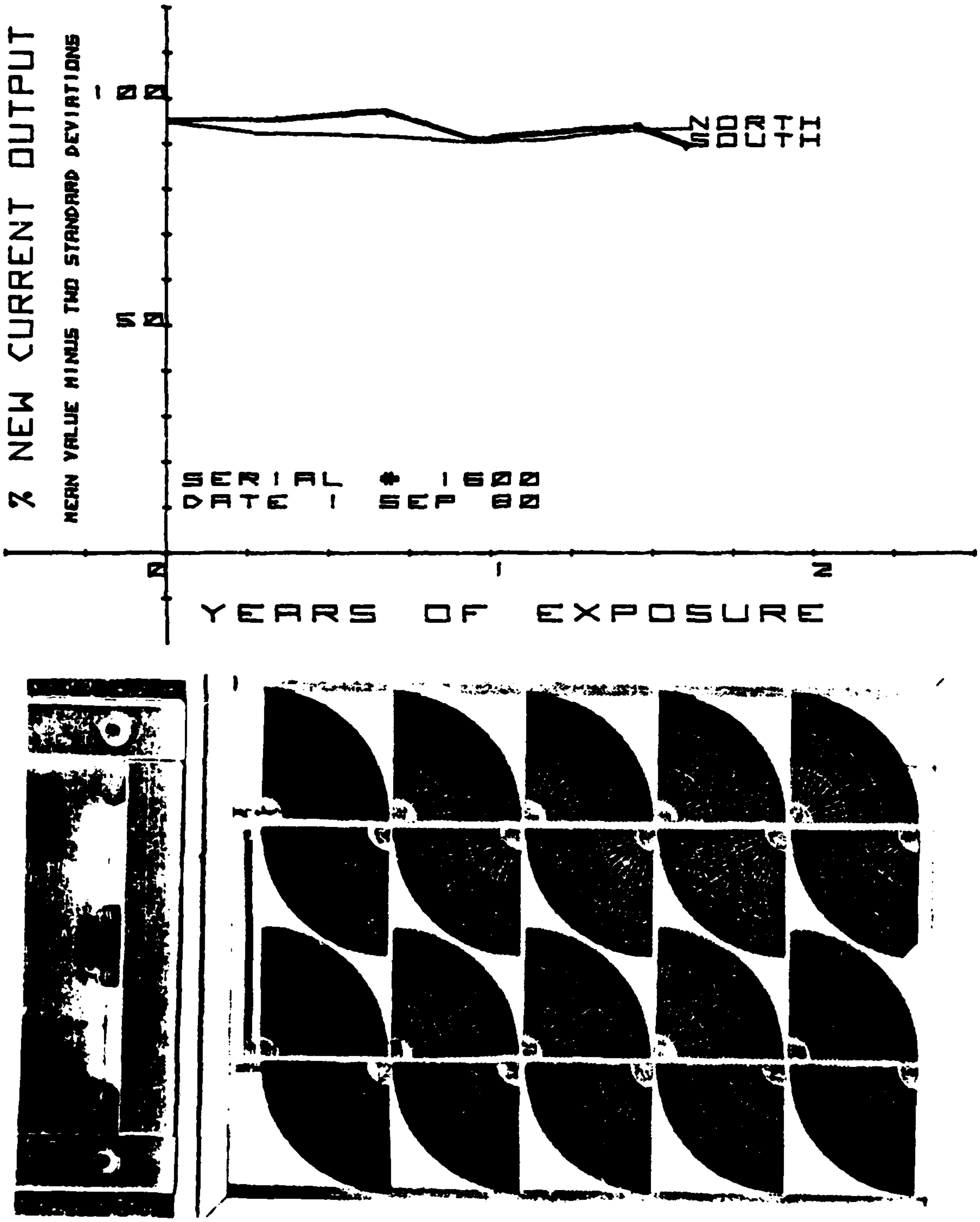


FIGURE 20. 1600 SERIES DATA SHEET

1600 SERIES PANEL - COMMENTS

This panel is of rigid lamina envelope construction with a tedlar substrate and a low-iron Sunadex glass cover. The cells are 75mm quarter cells with copper alloy interconnects. The panels sealant is polyvinyl butyrl with a thin tedlar sheet used as a moisture barrier. The frame is anodized aluminum with a connection plug for termination. The connector, as received, was not properly sealed and had to be modified for marine environment use.

Electrically and visually, these panels have not shown any degradation.

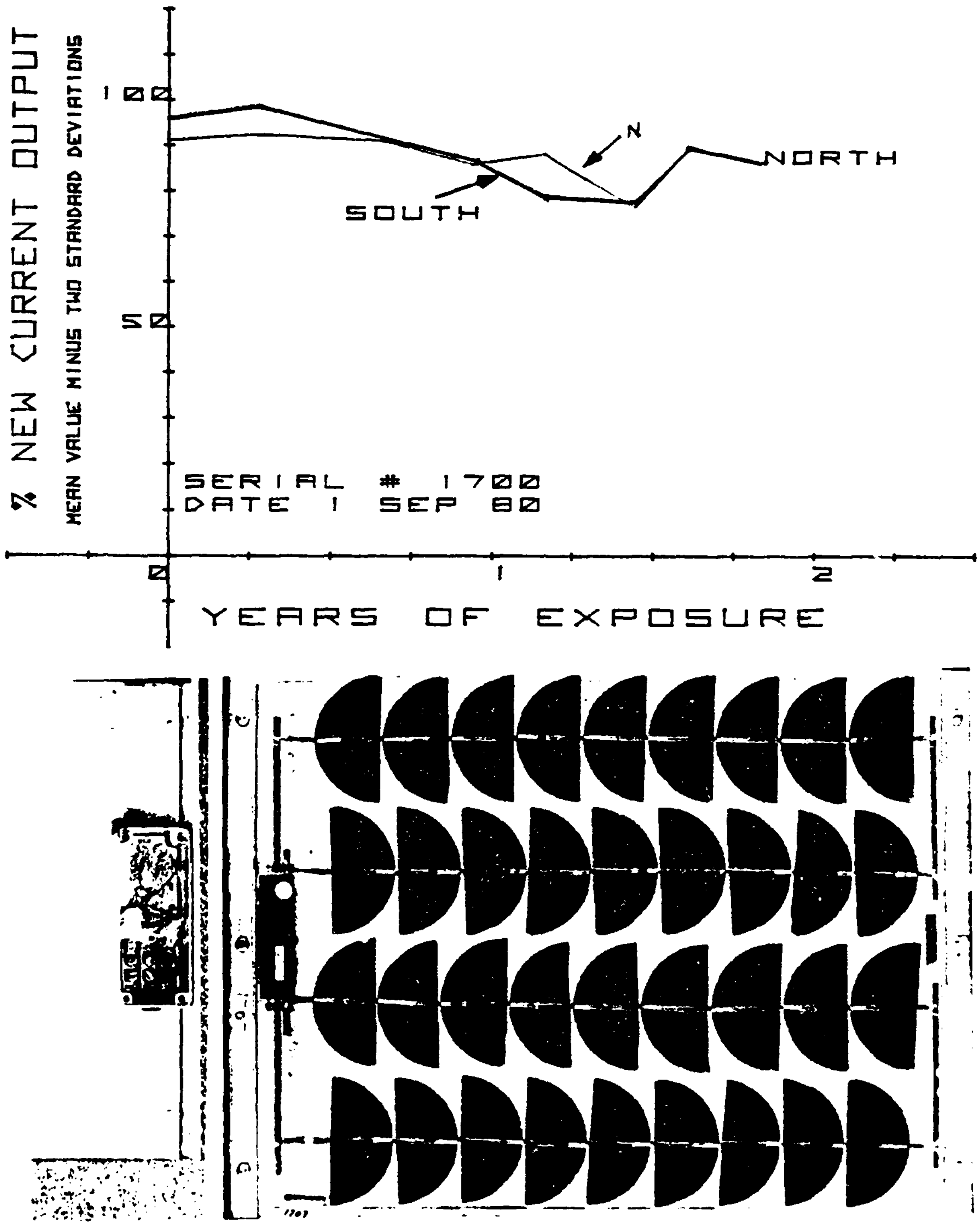
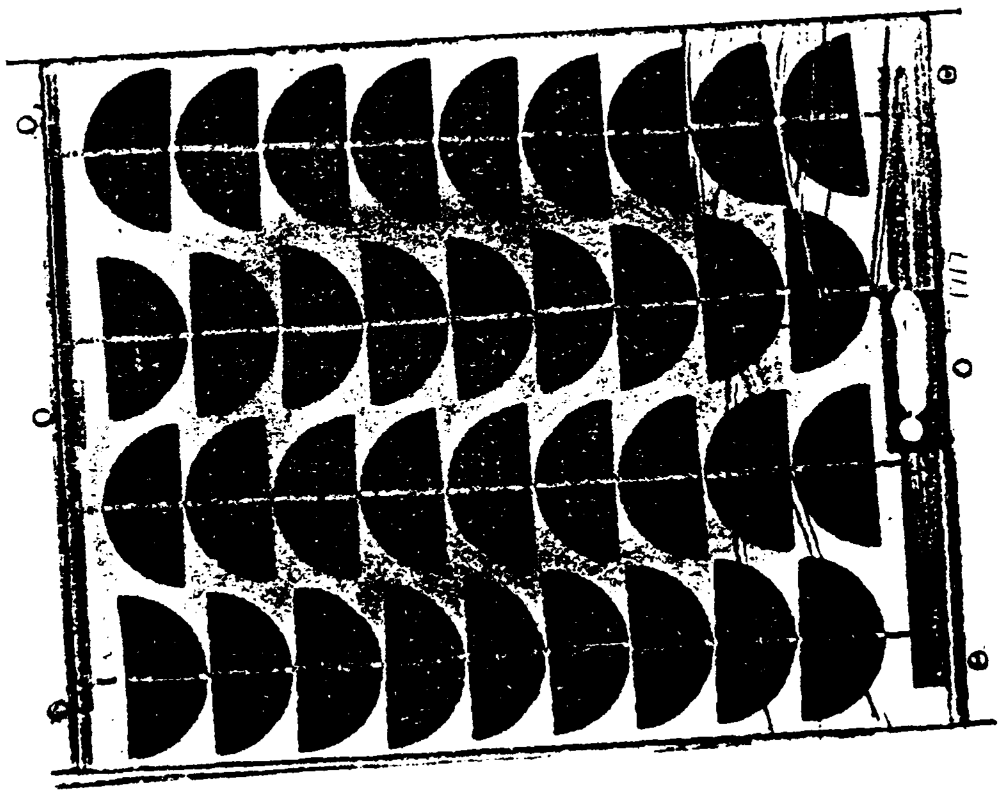


FIGURE 21. 1700 SERIES DATA SHEET

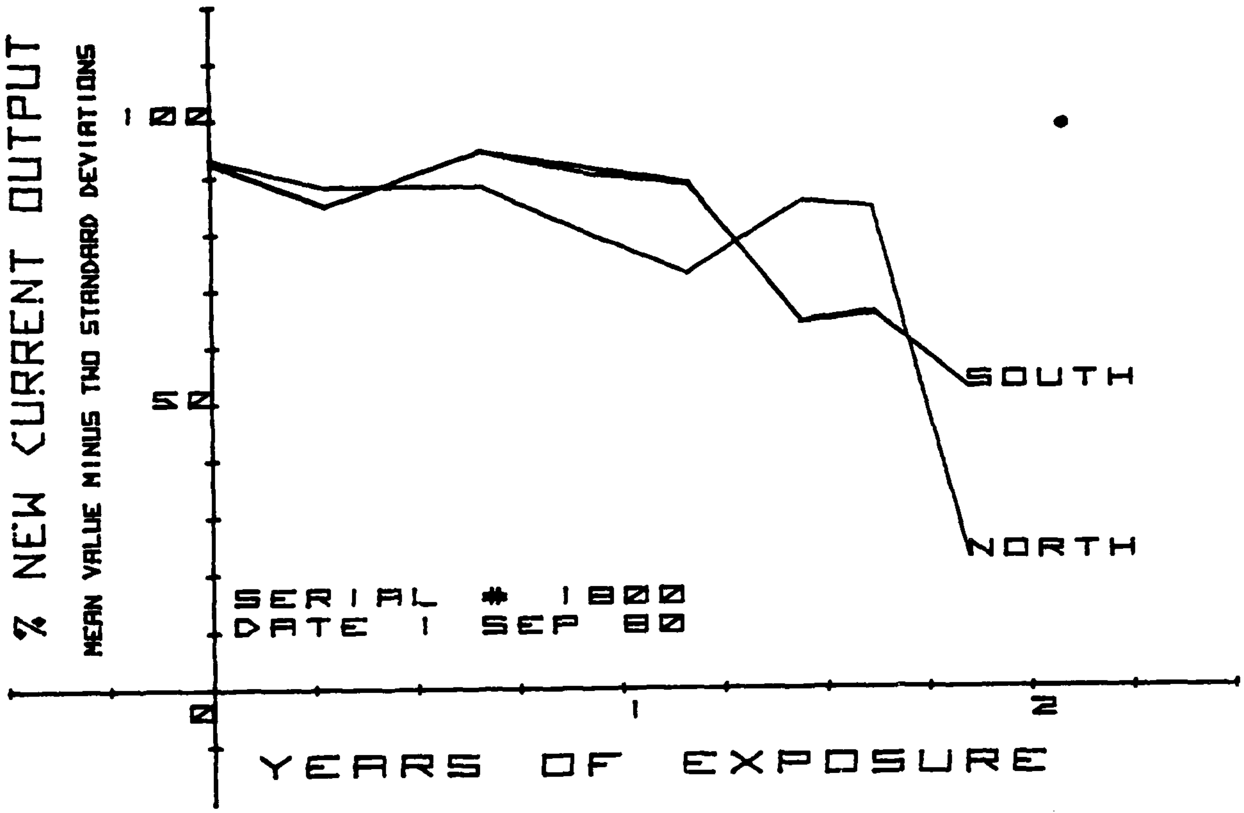
1700 SERIES PANEL - COMMENTS

This panel is of rigid lamina envelope construction with a tempered glass cover and an anodized aluminum substrate. The interconnect material between the 55mm half cells is a copper strip. The sealant material is a two-part RTV silicone rubber. A metal box on the back of the array houses the terminals which did not need modification for marine environment exposure.

No panels have shown any electrical failure or degradation to date; however, the panels appear to be optically degrading. (See photo below.) Degradation is discoloration of the RTV sealant probably due to excessive heating. Electrical degradation appears to be imminent due to the extent of the discoloration. NOTE: The glass cover was broken in handling.



SOUTHERN EXPOSURE



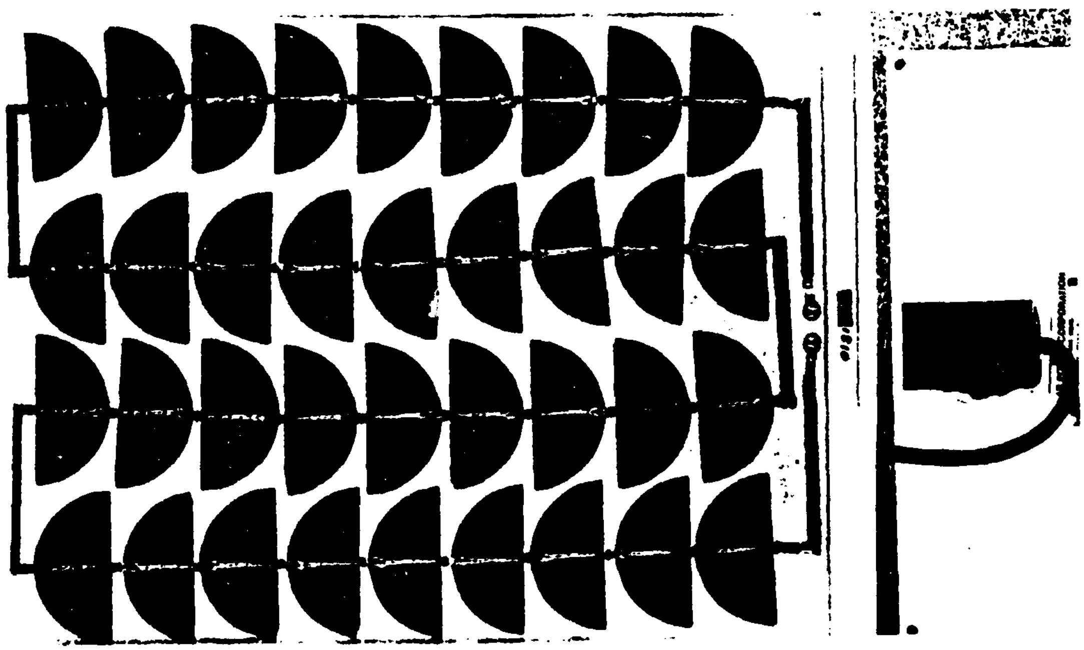
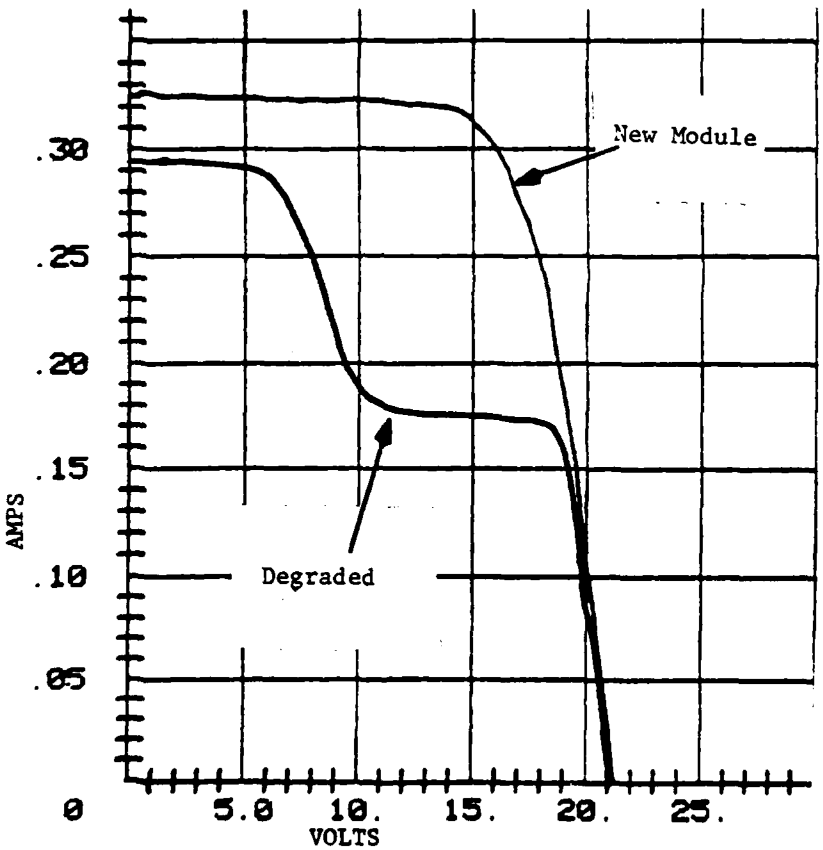


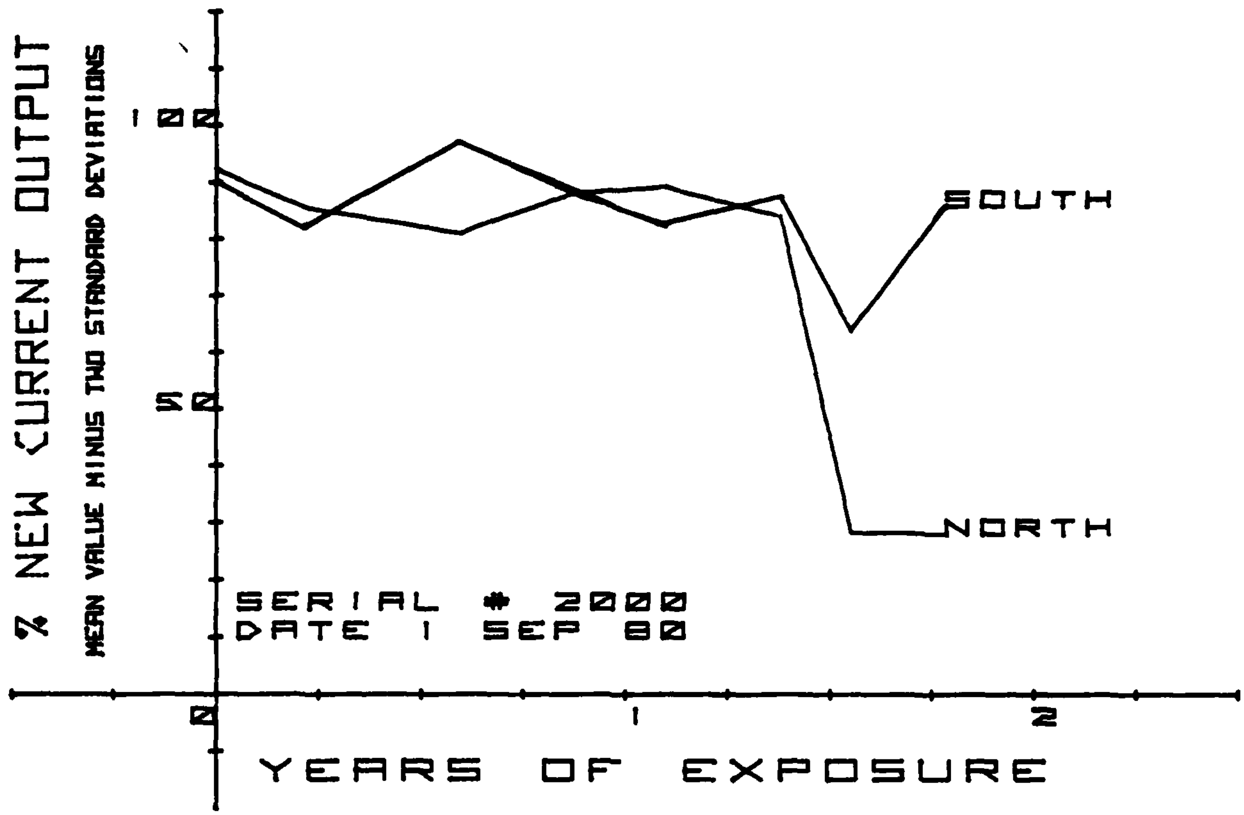
FIGURE 22. 1800 SERIES DATA SHEET

1800 SERIES PANEL - COMMENTS

This panel is conformally coated with a molded glass reinforced polyester substrate. The conformal coat is an RTV silicone rubber. The array has 55mm half cells with tin-plated copper interconnects. The terminals are located in a junction box which is bonded to the back of the array. This termination technique requires no modification for use in the marine environment. This panel is virtually identical to the 1100 series with the exception of the small cell size.

One panel of this type has failed and four panels are degraded. The I-V curve of one degraded panel is attached. The source of the degradation is believed to be an intermittent connection.





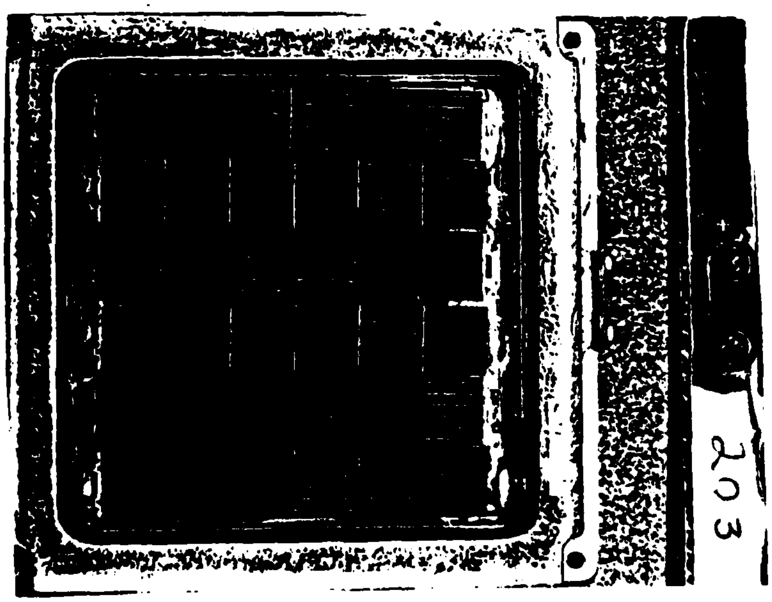


FIGURE 23. 2000 SERIES DATA SHEET

2000 SERIES PANEL

This is a conformal substrate array with a soda lime glass cover. The glass cover of this array fits inside a corrosion resistant aluminum frame. The 20mmx20mm square cells are bonded to the back side of the glass cover with several layers of RTV. Between the aluminum back of the array and RTV which covers the cells is an air gap. The terminals for this array are stainless steel screws mounted on the top of the array and held by epoxy. For use in the marine environment, the terminals for this array were sealed with heat shrink.

One panel in the northern marine environment failed due to the frame splitting below the terminal. Some clouding of the RTV sealant of these panels has been observed at both exposure sites but it is not considered to be detrimental in the short term.

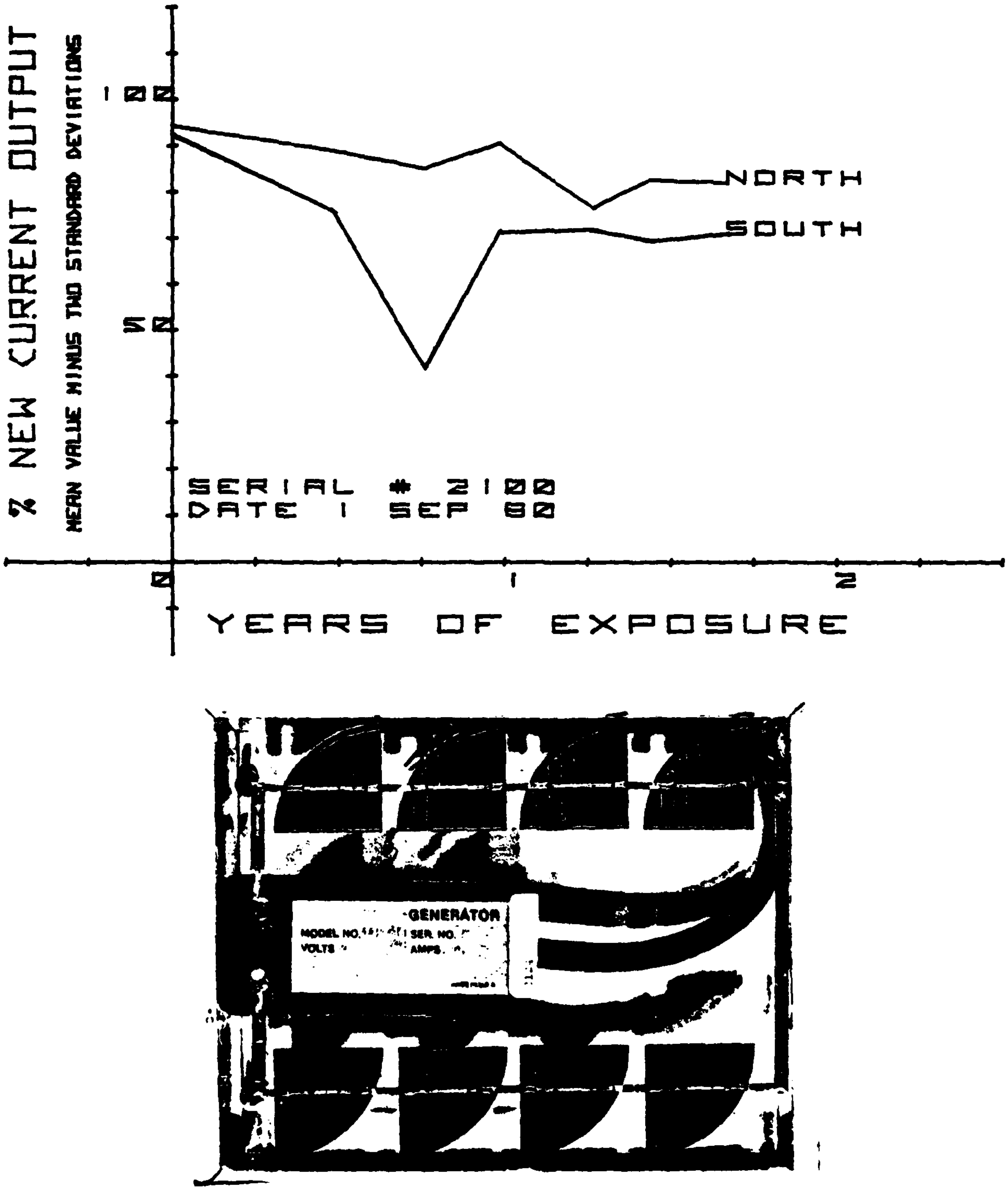


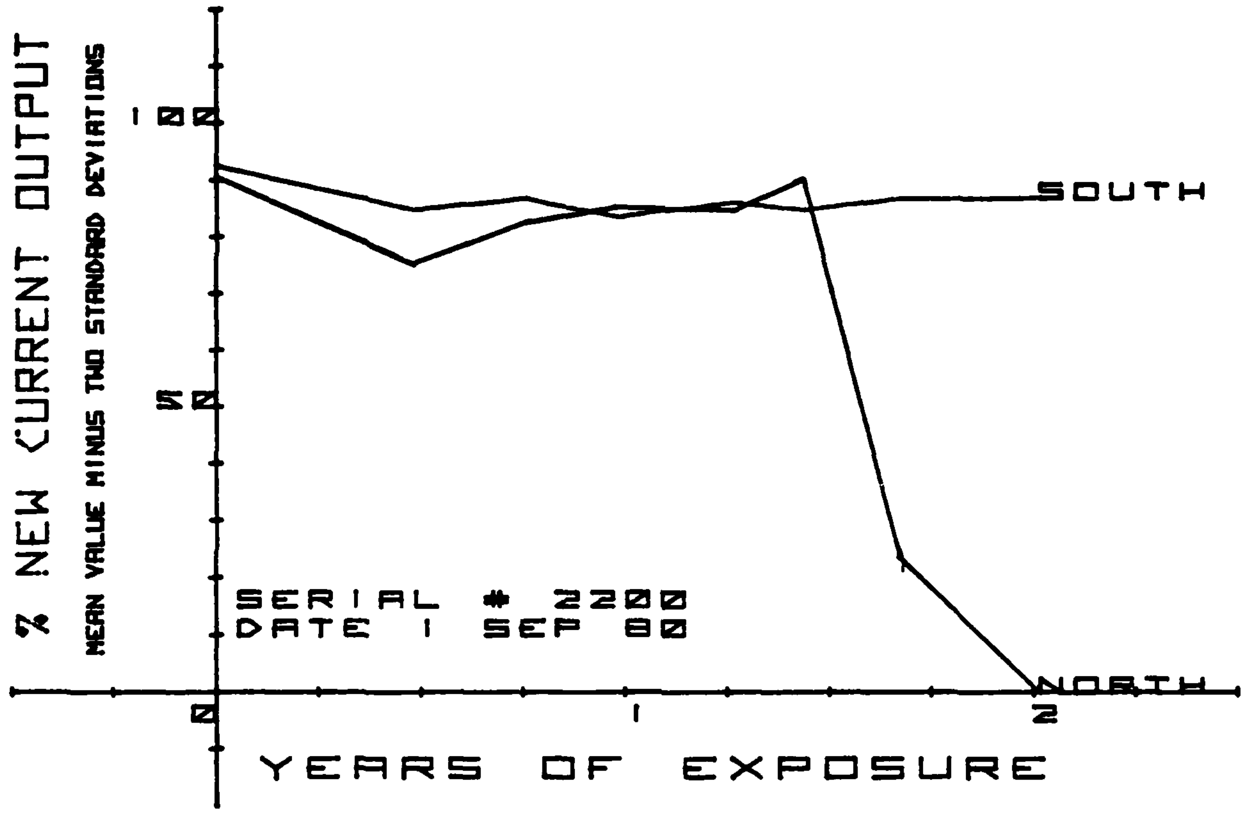
FIGURE 24. 2100 SERIES DATA SHEET

2100 SERIES PANEL - COMMENTS

This panel is of film laminate construction with a glass substrate and a glass cover. The sealant is Dow Corning 184 Silicon. The 75mm quarter cells are held in place by foam tape and interconnected with .004 tin/copper interconnects. The panel has an aluminum frame with a junction box on the back for termination.

Three panels are showing discoloration where the terminals feed through to the junction box. The discoloration has caused some electrical degradation.

The drop in current output at nine months was probably due to measurement error.



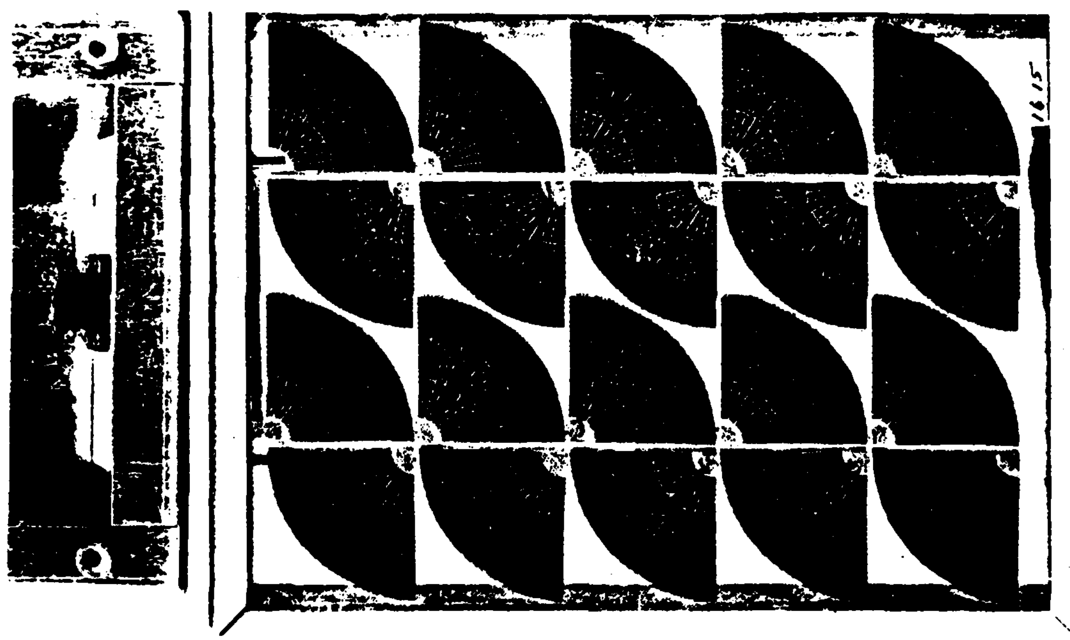


FIGURE 25. 2200 SERIES DATA SHEET

2200 SERIES PANEL - COMMENTS

This panel is of rigid lamina envelope construction with a tedlar substrate and a low-iron Sunadex glass cover. The cells are 75mm quarter cells with copper alloy interconnects. The panels sealant is polyvinyl butyrl with a thin sheet of tedlar used as a moisture barrier. The frame is anodized aluminum with a connector plug for termination. The connector, as received, was not properly sealed and had to be modified for marine environmental use. This panel is identical to the 1600 Series.

One panel has failed at the northern test site due to poor sealing of the junction box and a failure to properly seal the termination wires where they exist the encapsulation system.

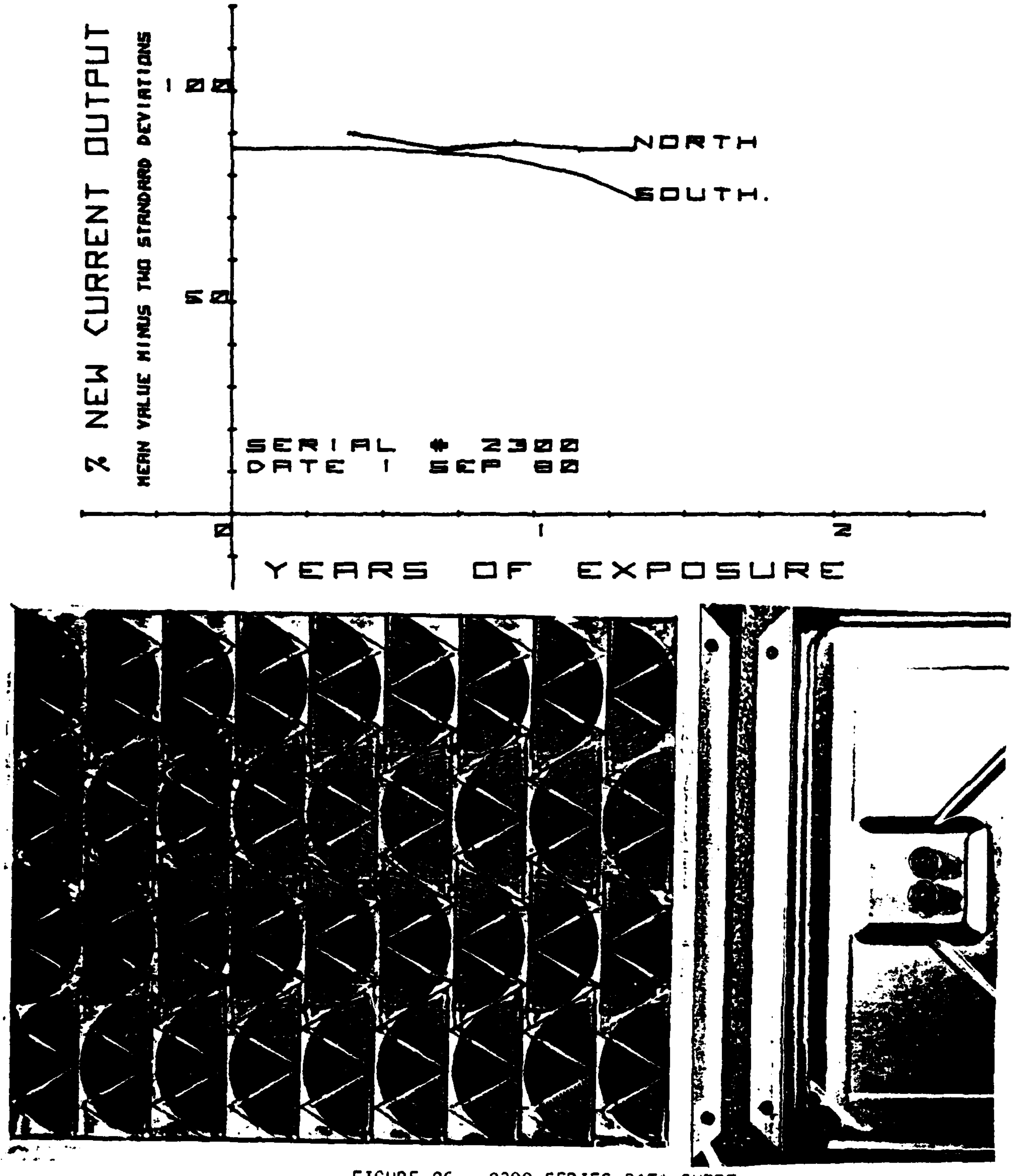


FIGURE 26. 2300 SERIES DATA SHEET

2300 SERIES PANEL - COMMENTS

This panel is of rigid lamina envelope construction with a tempered glass cover and a stainless steel substrate. The panel has 75mm half cells with Kapton laminated onto copper interconnects. The panel sealant is a non-hardening two-component silicone compound. The array terminals are two exposed posts on the back of the array. These terminals had to be coated prior to deployment in the marine environment.

Some discoloration probably due to water penetration is evident at the exposure facilities. No electrical degradation is expected in the short term due to the water penetration.

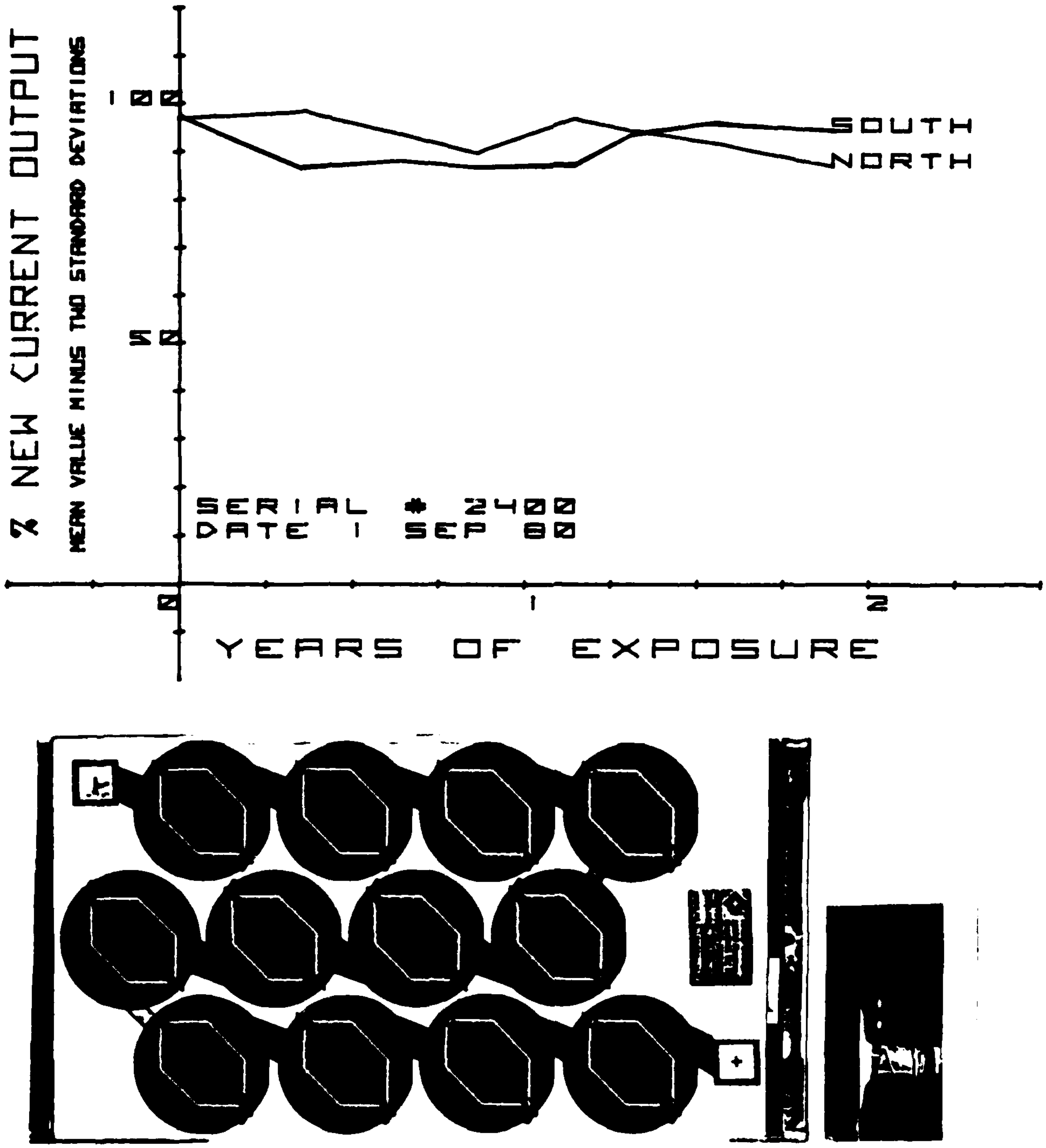


FIGURE 27. 2400 SERIES DATA SHEET

2400 SERIES PANEL - COMMENTS

This panel is of conformal substrate construction with a Pyrex glass cover and a white tedlar on polyvinyl butyrl substrate. The 75mm cells have solder plated copper interconnects. The panel sealant is polyvinyl butyrl. The panel has an stainless steel frame and mounting back. The array terminals are supported by the tedlar substrate. Holes have been cut through the aluminum back for access to the terminals. The terminals on this array are a problem. Several terminals have fallen off due to both poor soldering and poor mechanical support from the tedlar substrate.

Electrically, the panels have not shown any significant degradation. Three of the northern panels and four southern panels have discolored grids indicating corrosion from moisture penetration of the PVB sealant.

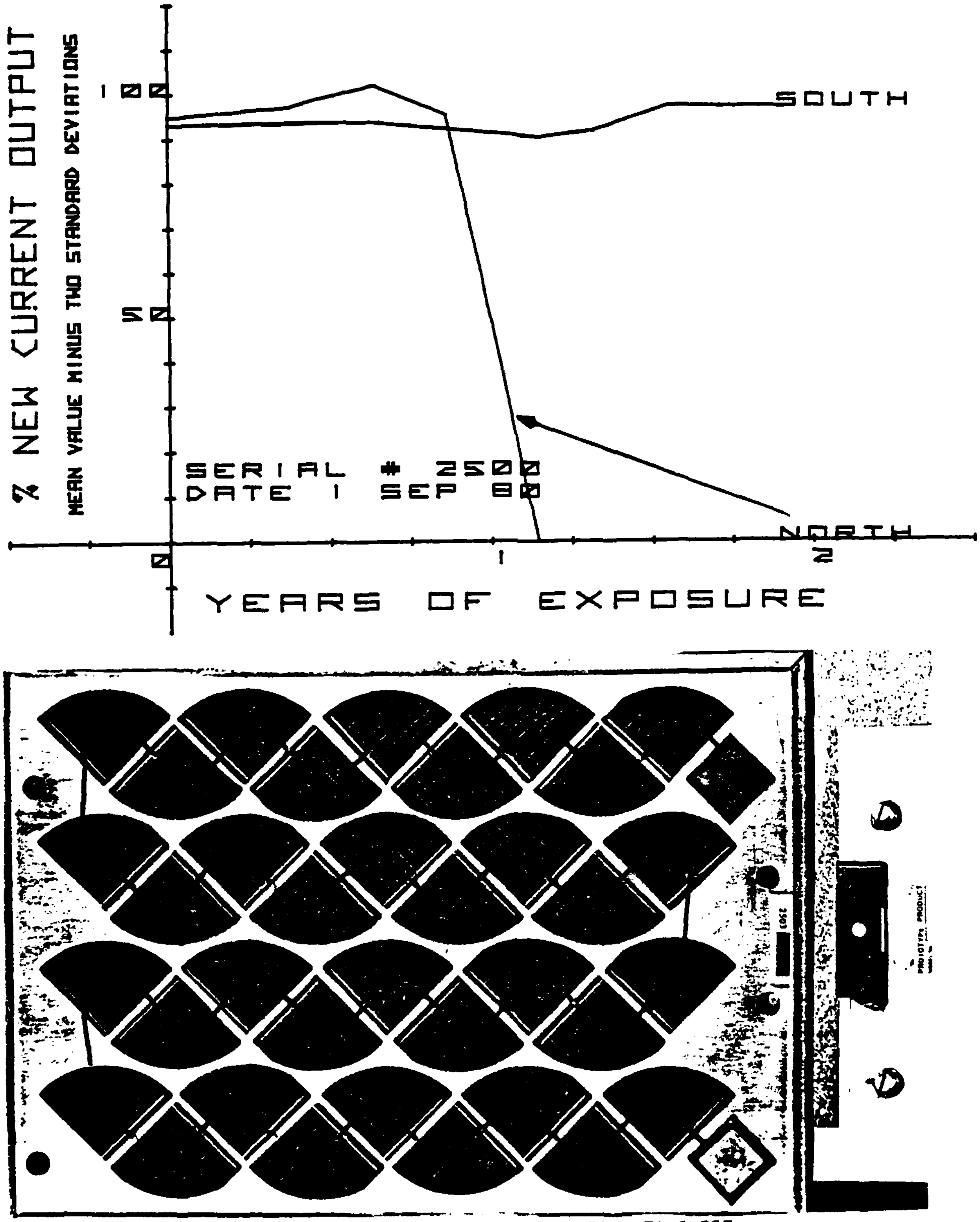
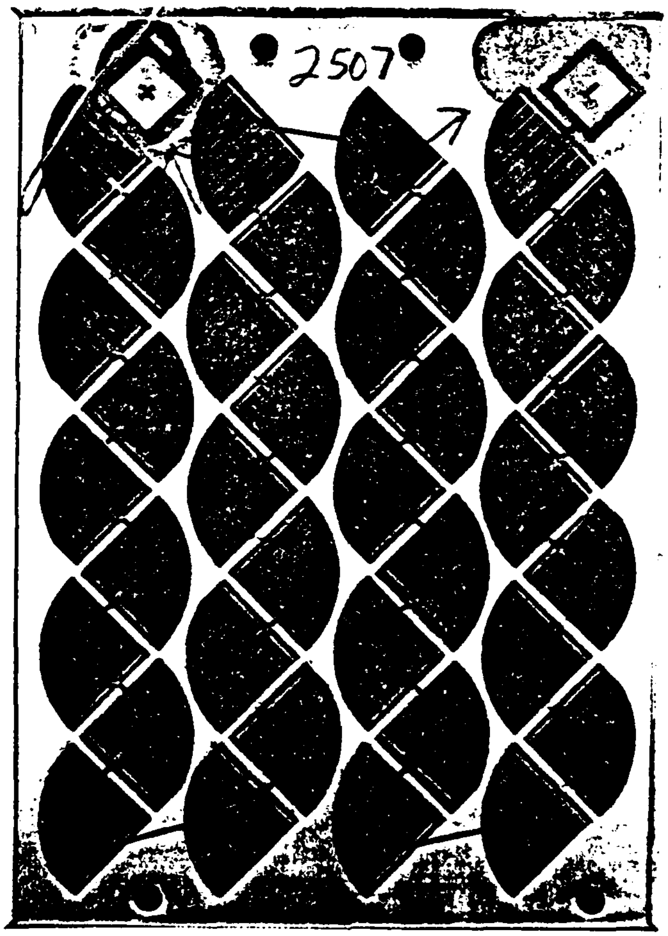
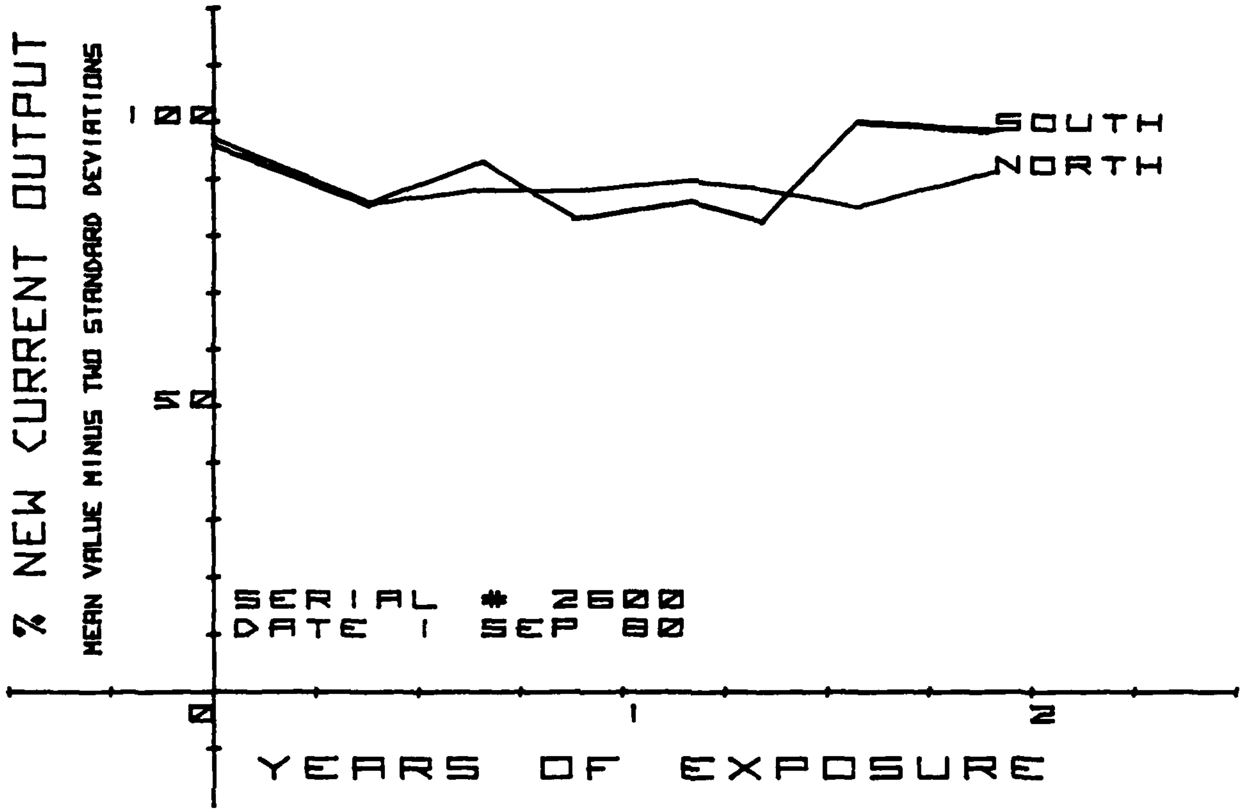


FIGURE 28. 2500 SERIES DATA SHEET

2500 SERIES PANEL - COMMENTS

This panel is of conformal coat envelope construction with a clear tedlar cover used as a vapor barrier and an aluminum substrate. The cells are 75mm quarter cells with solder plated copper interconnects. Sealant material is polyvinyl butyrl. The thin aluminum substrate does not have sufficient strength to support the terminal posts on the back of the array. Cracks have developed which allow water to enter the array. Three panels have failed to date due to corrosion from salt water intrusion around the terminals and the screws which hold the mounting brackets to the substrate. (See photo below.)





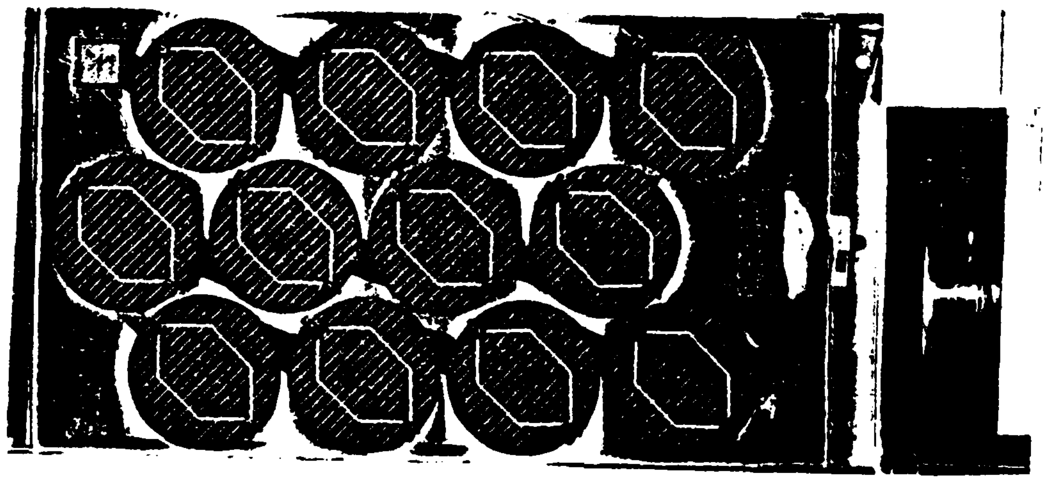
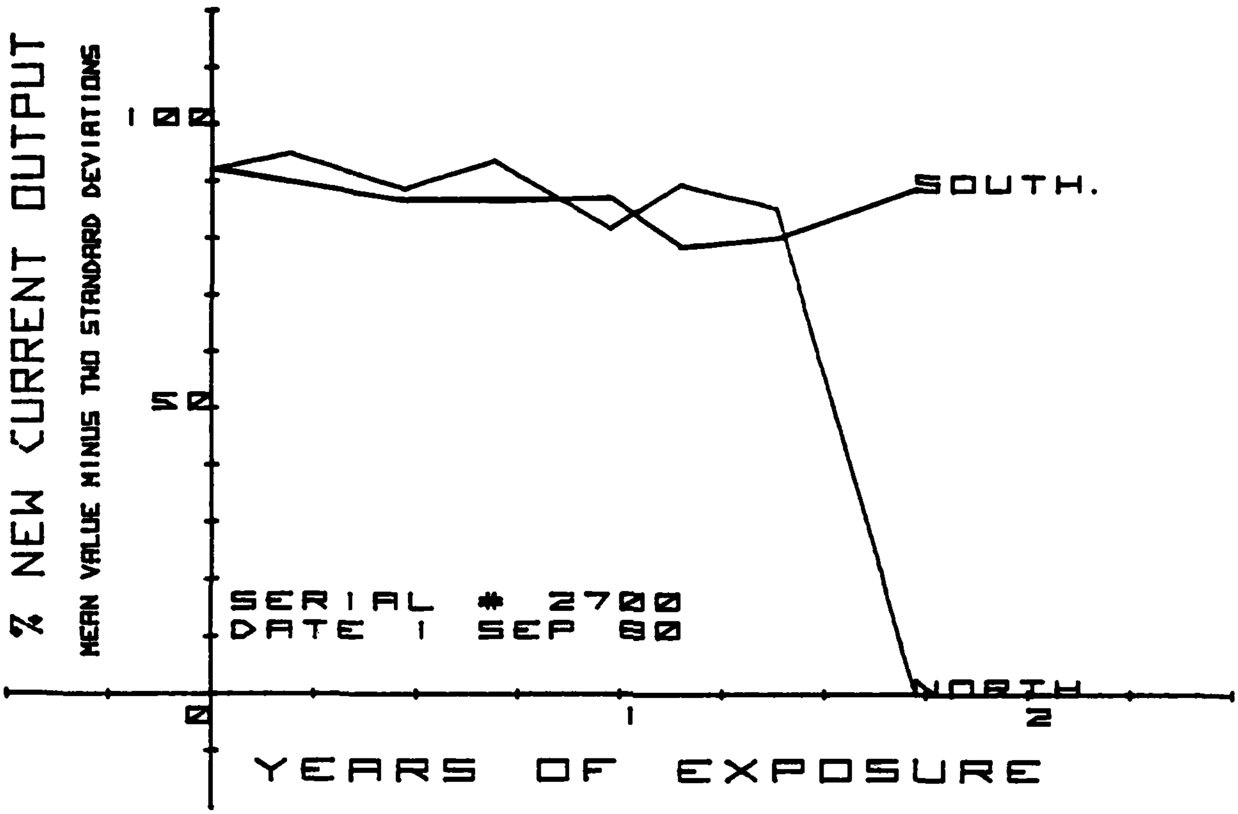


FIGURE 29. 2600 SERIES DATA SHEET

2600 SERIES PANEL - COMMENTS

This panel is of conformal substrate construction with a Sunadex glass cover and a white tedlar on polyvinyl butyrl substrate. The 75mm cells have solder plated copper interconnects. The panel sealant is polyvinyl butyrl. The panel had a stainless steel frame and mounting bracket. This panel is identical to 2400 series with the exception of the cover material. The terminal problems are the same as the 2400 series.

Electrically, these panels have not shown any significant degradation. Visually, three northern panels and two southern panels have discolored grids indicating moisture penetration of PVB sealant.



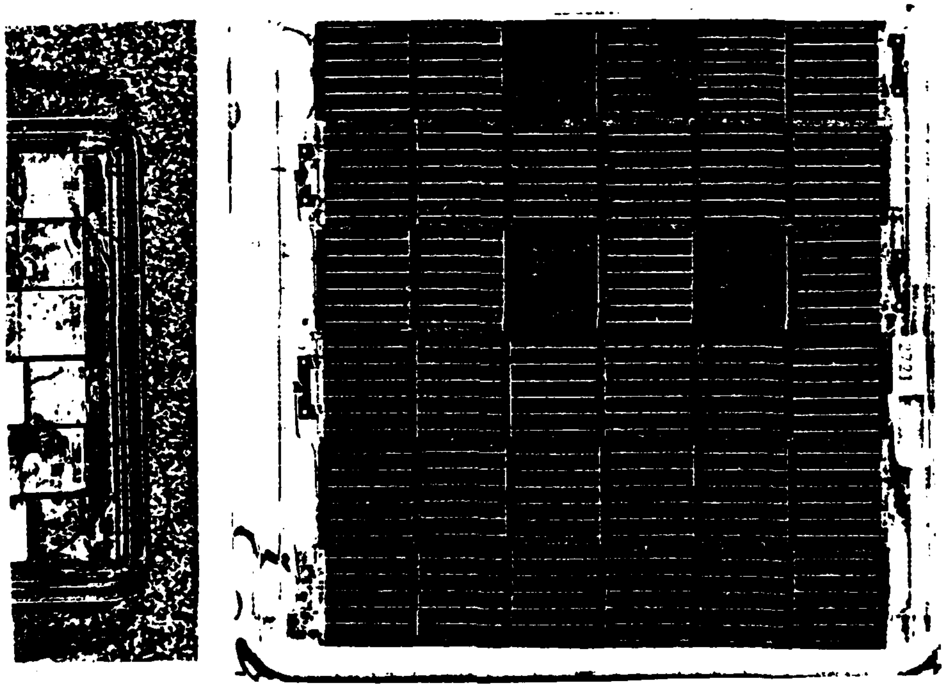
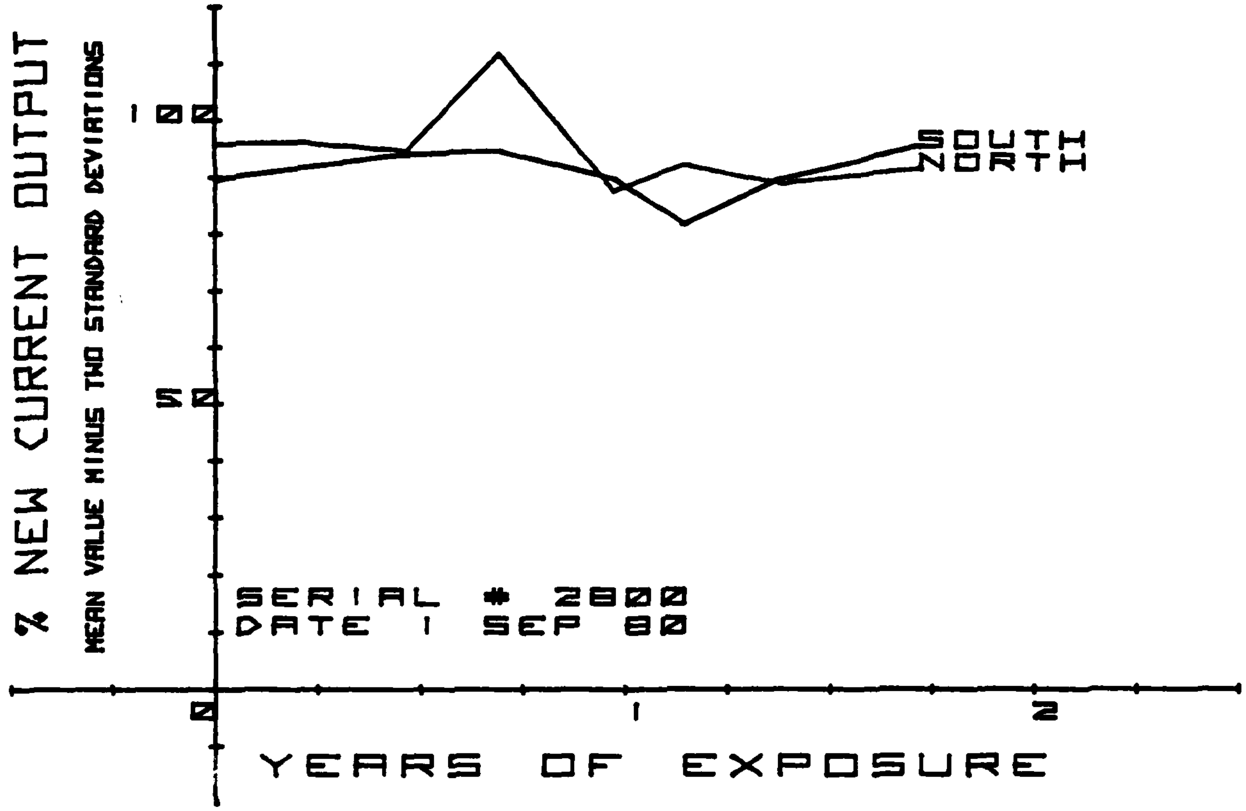


FIGURE 30. 2700 SERIES DATA SHEET

2700 SERIES PANEL - COMMENTS

This panel is a specialized design with a soda lime glass cover. The 20mmx20mm square cells are bonded to the back side of the glass cover. Several layers of GE 625 RTV are then poured over the cells to protect them. No other substrate materials other than RTV are used. Two pigtails form the terminals. The panel is a 2000 series panel without the frame.

One panel of this series was damaged in handling and subsequently failed. The remainder of the panels have shown no electrical or visual degradation.



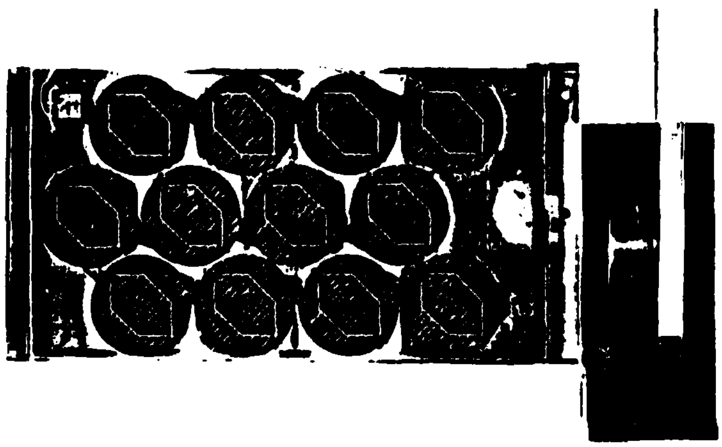


FIGURE 31. 2800 SERIES DATA SHEET

2800 SERIES PANEL - COMMENTS

This panel is of conformal substrate construction with a Sunadex glass cover and an aluminum foil on polyvinyl butryl substrate. The aluminum foil acts as a moisture barrier. The 75mm cells have solder plated copper interconnects. The sealant is polyvinyl butyrl. The panel has a stainless steel frame identical to the 2400 series panel. This panel also has the terminal problems of the 2400 series.

Electrically, the panels have not shown any significant degradation; however, there is significant visual degradation on all panels due to the aluminum foil debonding and PVB deterioration.

7.0 PRESSURE, IMMERSION, TEMPERATURE (PIT) TESTING

Several years of research at the Coast Guard Research and Development Center have been devoted to developing a laboratory test procedure that would permit the rapid identification of solar photovoltaic panels that are suitable for use in the marine environment. This effort has taken place concurrently with the Natural Environment Exposure Test (NEET) and has evolved into the Pressure, Immersion, Temperature (PIT) test procedure.

7.1 PIT Test Procedure

The test procedure consists of the following steps:

a. Measure Illuminated I-V Curve I: The current versus voltage curve is obtained at the commercial solar simulator owned by Solar Power Corporation in Boston, MA. Each panel, prior to testing of any kind, is placed on the solar simulator to obtain a baseline I-V curve against which the effects of any subsequent tests can be noted.

b. Pre-Exposure Test: Each panel is subjected to alternate spraying with fresh water and drying (using eight GE 275-watt sunlamps and four GE 40BL ultraviolet lamps). This pre-exposure test continues for 49 days.

c. Measure Illuminated I-V Curve II: When compared to Curve I, this curve reflects the effects of the pre-exposure on the panel and represents the state-of-the-panel prior to placing it in the PIT test chamber. This curve is obtained at Solar Power Corporation.

d. PIT Test: Each panel is placed inside the PIT test chamber and subjected to the following sequence of stresses which defines one 28-minute cycle:

1. Immersed in 50°C salt water
2. Pressurized to 5 psig five times
3. Immersed in 5°C salt water
4. Pressurized to 5 psig once

Begin cycle again with immersion in 50°C salt water. Each panel is subjected to 2000 cycles of the sequence of stresses.

5. Measure Illuminated I-V Curve III: This curve represents the state-of-the-panel after PIT cycling, which can be compared to the curve representing the state prior to the PIT cycling and to the original state curve. This curve is obtained at Solar Power Corporation.

6. Failure Analysis: Panels that fail during any part of the testing sequence are disassembled, the cause of the failure identified (if possible), and a failure report is prepared.

7.2 PIT TEST RESULTS

Table 4 lists a summary of photovoltaic array performance after 2000 cycles of PIT testing. Table 4 is broken down into the following categories:

Number tested - Unequal sample size is due to the ongoing nature of the PIT test which will not be completed until 1 January 1981.

Electrical Failures - An electrical failure is defined as 60% or less test current output when compared to the test current output prior to testing.

Electrical Degradation - Electrical degradation is defined as less than 80% but greater than 60% test current output when compared to the test current output prior to testing.

Visual Degradation - Degradation processes that are visible to the eye but have not caused electrical degradation are classified as visible degradation. Processes included are corrosion on interconnects, cell grids, and water in the interior of the panel. Visual degradations are expected to result in electrical degradation in a short time.

Total Undesirable - This represents the total of the electrical failure, electrical degradation and visual degradation columns.

Observation - This column lists the reasons for the undesirable behavior observed.

Figure 32 graphically presents this data grouped by generic panel type.

TABLE 4

SUMMARY OF PHOTOVOLTAIC PANEL PERFORMANCE AFTER 2000 CYCLES OF PIT TESTING

	NUMBER TESTED	ELECTRICAL(1) FAILURES	ELECTRICAL(2) DEGRADATION	VISUAL(3) DEGRADATION	TOTAL UNDESIRABLE	OBSERVATION
0500	8	2	0	3	5	Water in the interior of the panel
1100	5	1	2	0	3	Corrosion at terminal, cracked cells
1200	6	0	0	0	0	
1400	6	0	0	0	0	
1500	7	1	0	0	1	Poor seating at termination
1600	7	2	0	5	7	Poor seating at terminal box allows water intrusion
1700	7	0	0	0	0	
1800	7	2	2	1	5	Cracked cells, corrosion on cells
2000	7	0	0	1	1	Water in interior of panel
2100	7	0	0	0	0	
2200	8	2	0	6	8	Poor sealing at terminal box allows water intrusion
2300	6	0	0	0	0	
2400	6	0	0	2	2	Weakened substrate at terminals
2500	7	4	0	3	7	Delamination between PVB pottant and tedlar cover
2600	6	0	0	4	4	Weakened substrate at terminals - substrate delamination
2700	5	5	0	0	5	Poor termination
2800	6	1	0	5	6	Breakdown of PVB pottant and aluminum vapor barrier

(1) Failure: 60% or less test current output
(2) Degradation: less than 80% but greater than 60% test current output
(3) Degradative processes that are visible to the eye but have not caused electrical degradation

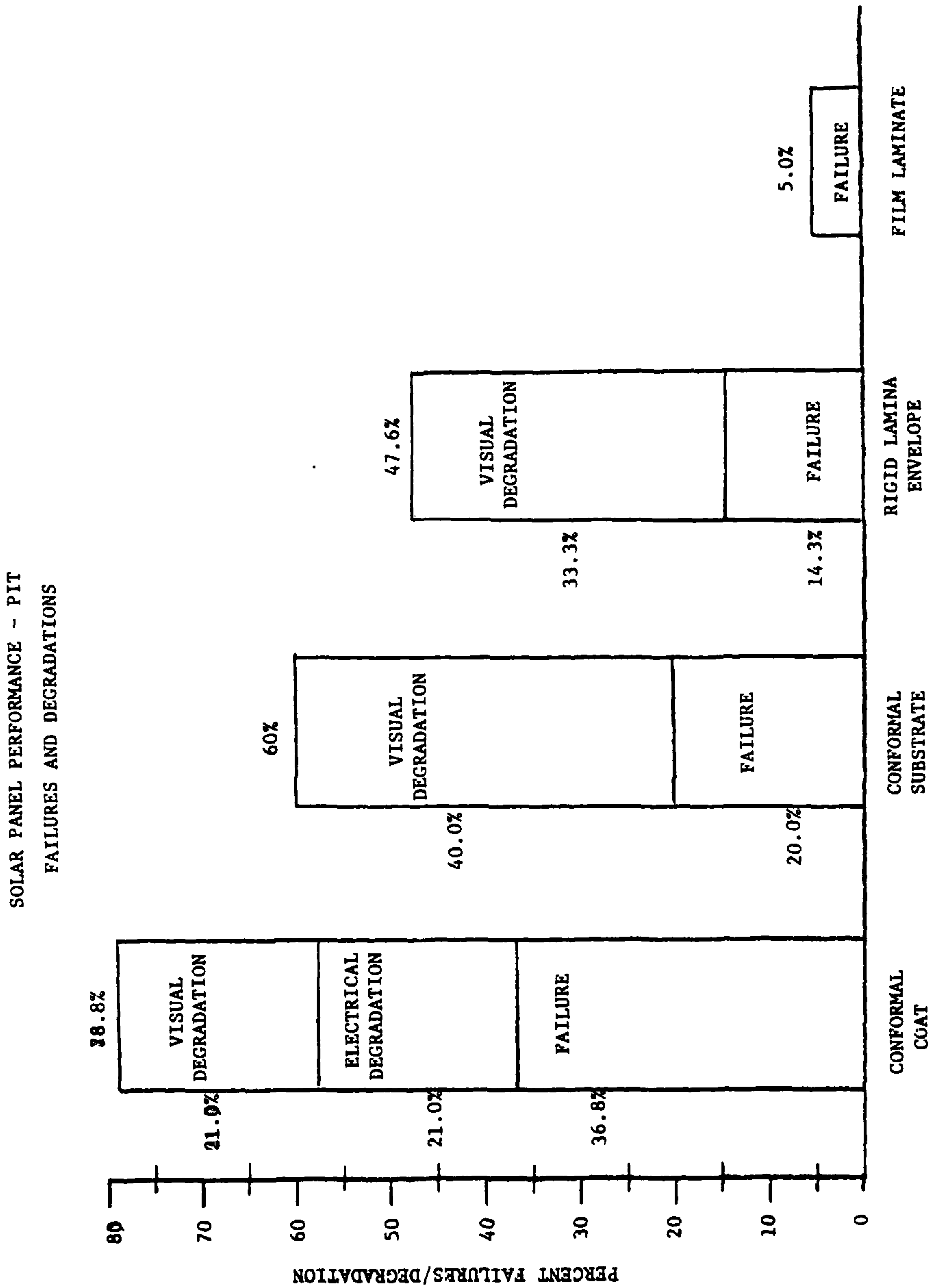


FIGURE 32. SOLAR PANEL PERFORMANCE (PIT)

8.0 CONCLUSIONS AND RECOMMENDATIONS

Although the PIT testing sequence will not be completed until 1 January 1981, sufficient information from both the marine environment exposure test and the PIT test is available to make some conclusions on the material and construction techniques that are acceptable for use in the marine environment.

8.1 Construction Techniques Recommendations

Table 5 is a composite summary of solar photovoltaic panel performance in both the Natural Environment Exposure Testing (NEET) and the Pressure, Immersion, and Temperature (PIT) testing. The entries in the columns represent the sum of electrical failures, electrical degradation, and visual degradation observed for a particular model.

Based on table 5, only two construction techniques have any models that have not shown any undesirable behavior. They are rigid lamina envelope (1200, 2300) and film laminate (1400) construction. Both these systems are recommended for use in the marine environment subject to the material recommendation in section 8.2.

Two construction techniques are not recommended:

Conformal Substrate - The primary objective with this form of panel construction is the lack of mechanical strength of the substrate. The substrate doesn't allow for the support of the terminals of the array. Consequently, cracks form around the terminals allowing the penetration of seawater into the interior of the panel. The material recommendation of a junction box termination (section 8.2.1) technique is not compatible with a conformal substrate array.

Conformal Coat - This technique has been subject to a very high percentage of failures. The problem appears to be related to thermal cycling of the arrays. The soft covering materials breakdown under thermal stress allowing salt water penetration or mechanical damage to the electrical system of the array.

Figure 33 presents this data graphically substantiating these conclusions and illustrating the comparison between PIT and NEET test results.

TABLE 5
COMPOSITE SUMMARY OF PANEL PERFORMANCE

	CONSTRUCTION TECHNIQUE	TOTAL MARINE ENVIRONMENT (1)	TOTAL PIT TESTING (2)
0500	Rigid Lamina Envelope	7 of 20	5 of 8
1100	Conformal Cover	16 of 20	3 of 5
1200	Rigid Lamina Envelope	0 of 20	0 of 6
1400	Film Laminate	0 of 20	0 of 6
1500	Film Laminate	1 of 20	1 of 7
1600	Rigid Lamina Envelope	0 of 20	7 of 7
1700	Rigid Lamina Envelope	13 of 20	0 of 7
1800	Conformal Cover	5 of 20	5 of 7
2000	Conformal Substrate	1 of 20	1 of 7
2100	Film Laminate	3 of 20	0 of 7
2200	Rigid Lamina Envelope	1 of 20	8 of 8
2300	Rigid Lamina Envelope	0 of 16	0 of 6
2400	Conformal Substrate	7 of 20	2 of 6
2500	Conformal Cover	3 of 20	7 of 7
2600	Conformal Substrate	5 of 20	4 of 6
2700	Conformal Substrate	1 of 20	5 of 5
2800	Conformal Substrate	20 of 20	5 of 6

(1) Total number of panels exhibiting undesirable behavior resulting from marine environment exposure

(2) Total number of panels exhibiting undesirable behavior resulting from 2000 cycles of Pressure, Immersion, and Temperature (PIT) testing

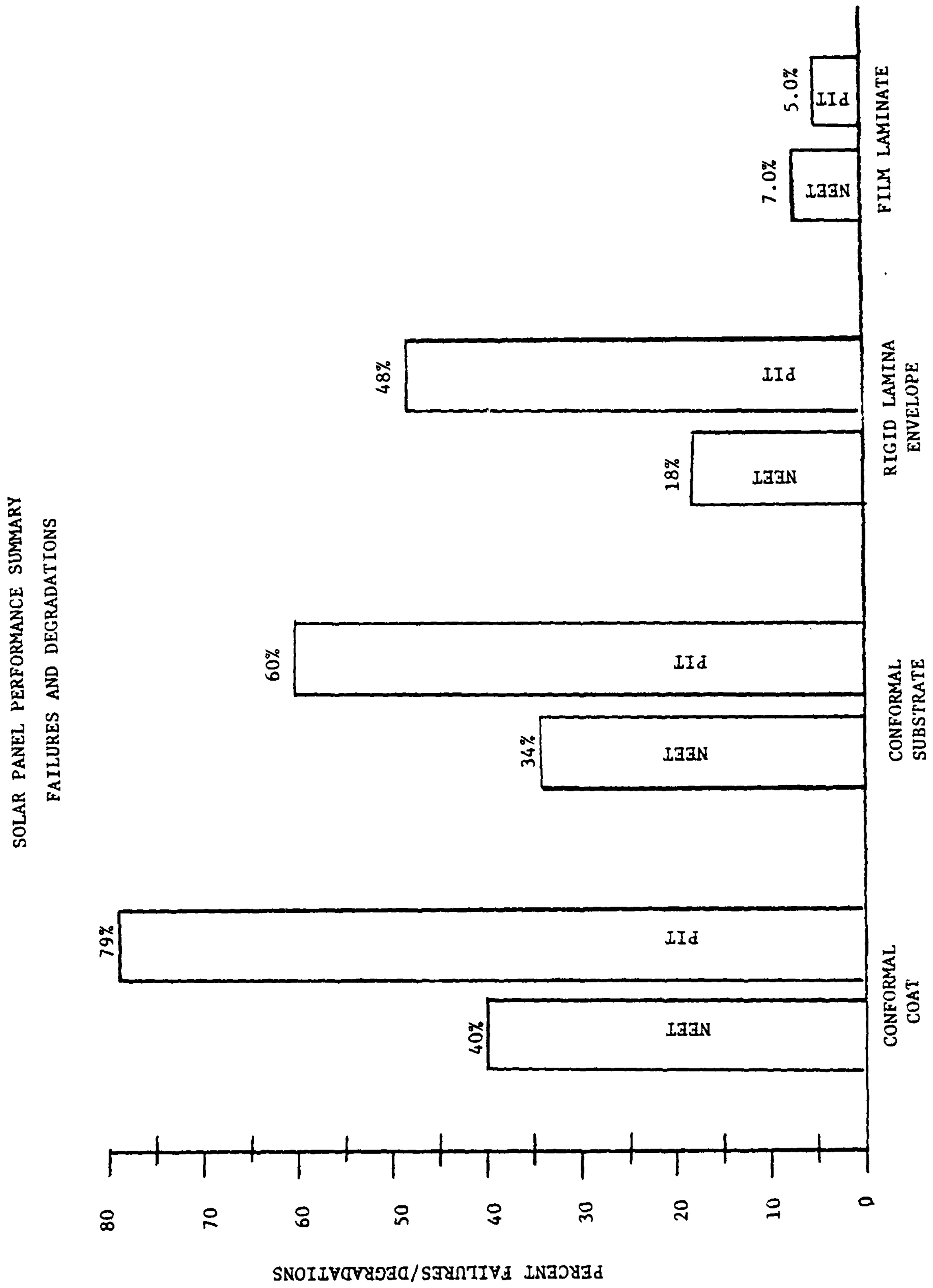


FIGURE 33. SOLAR PANEL PERFORMANCE COMPARISON (PIT AND NEET)

8.2 Material Recommendations

Although the number of electrical failures has not been sufficient to perform rigorous statistics comparisons between materials, trends are apparent which allow some conclusions and recommendations.

8.2.1 Termination

The terminals are the most vulnerable area of the panel to the effects of the marine environment. The most common problem with the panels on test has been poor termination techniques. No particular panel had an entirely satisfactory termination technique; consequently, a special technique for the marine environment is recommended. The recommended technique is a terminal box of moisture-proof "NEMA 4X" type minimum construction. A compatible stuffing tube for the external leads should be part of the terminal box. Connections should be made on a "barrier" terminal strip with corrosion-proof #10 screws. Wires used should not be Teflon[R] coated to prevent water intrusion where the Teflon[R] fails to seal with the pottant of the panel. Wires should have ring lugs that are crimped and soldered. Both terminals of the panels should penetrate the encapsulant near the same point to allow the use of a single terminal box. The terminals should be separated at least 3/4 inch where they enter the terminal box. Penetration of the substrate of the encapsulant should not take place within 1/2 inch of any edge of the panel. The terminal box should be permanently mounted by welding, bolting, or epoxy. Dow Corning RTV 3145, or the equivalent, is recommended for potting material. At least 1/4-inch thickness of RTV should coat any connections.

8.2.2 Sealant

RTV silicone rubber is the recommended cell sealing material. Polyvinyl butryl (PVB) is not recommended due to its permeability by water. The use of PVB places an extra burden on the encapsulation system as it provides less protection to the electrical system once water breeches the encapsulation system. In the 2500 series panel, once water leaks into the panel they fail almost immediately while the 1400's have had five cracked cover plates for over a year but the RTV is still protecting the cells. The 2700's, with no vapor barrier or substrate except RTV, have shown no degradation after more than a year of exposure to the marine environment. RTV's GE615, Dow Corning 3145 and Dow Corning 184 (or the equivalent) are recommended.

Panels that have a very thin layer of sealant between the cover plate and the substrate enclosing the cells (1400, 1200) appear to be performing superiorly. Two possible explanations are:

a. Thin layers of sealant minimize the thickness through which the heat generated by the cell must be conducted.

b. Thin layers have a smaller net displacement on thermal cycling than thicker layers with the same coefficient of expansion. The smaller displacements may minimize delamination and debonding.

The only panel with a thick layer of sealant still not exhibiting any degradation (2300) is unique in that its sealant is liquid. Liquid sealant does not exhibit the expansion and contraction on thermal cycling that a solid sealant does.

8.2.3 Cover Plate

The recommended material is glass. No failures other than panels cracked during installation can be attributed to the glass cover material. The extremely poor behavior of RTV conformal covered panels (1100, 1800) and the PVB with a clear Tedlar vapor barrier panel (2500) eliminate these techniques from consideration. Failures observed with soft pottant covered panels included cracked cells, corrosion from salt water intrusion, intermittent interconnects, delamination, and debonding. All these failures suggest that these materials have problems with the expansion and contractions of thermal cycling.

Further exposure will be needed to identify particular types of glass that have superior performance in the marine environment. Special plastics also appear to be acceptable although only Lexan(R) is presently on test.

8.2.4 Substrate

The substrate material must perform several functions in the marine environment:

a. It must provide some of the mechanical strength of the array. It must be able to withstand the stresses of the mechanical connection of the terminal box without cracking allowing water into the interior of the panel.

b. It must not be permeable to water and must act as a vapor barrier.

c. It must have thermal properties that allow the cells to operate at as low a temperature as possible. This reduced temperature increases the efficiency of the cells and reduces thermal stresses on the encapsulation system.

d. It must not be easily corroded by seawater.

Three materials used as substrates have shown superior performance (table 5). They are glass (1400), aluminum (1200) and stainless steel (2300).

The metallic substrates remove heat by conduction, have high mechanical strength which allows for ease of mounting on structures and provides good support for a terminal box. They are hampered by a different coefficient of expansion than the glass cover.

The glass substrate operates cooler than the metallic substrates as energy that is not incident on the cells passes on through the array. The glass substrate also allows the infrared radiation from the

heating of the cells to radiate away. The glass substrate presents difficulty in mounting and is vulnerable to impact shock. Coupled with a glass cover, the glass substrate should not produce differential expansions on the encapsulating system from thermal stresses.

8.2.5 Interconnects

Copper is the recommended interconnect material. It has been observed that wide interconnects between cells (2800) delay the degradation from salt water corrosion. Wide strip, wire mesh, and multiple strip interconnects are recommended as they all provide some redundancy in connection.

8.3 Aids to Navigation System Deployment

Reliability and effectiveness are overriding considerations in deciding on the large-scale operational deployment of solar photovoltaic charging systems on marine aids to navigation. Experience at the Coast Guard Research and Development Center indicates the panels are the limiting component in terms of reliability of the solar photovoltaic systems tested.[5] As the panels are the limiting factor, an investment in a superior panel will pay off in greatly enhanced reliability of the solar photovoltaic charging system.

As the photovoltaic panel is the most likely trouble spot in the system, a field measurement system of the panel could show large resource savings by reducing repeat visits to an aid and reducing the number of batteries damaged by under charging. A sophisticated standard cell, microprocessor-based system was proposed and rejected on the grounds of cost and the difficulty of access to the electrical system of the aid to navigation.

Presently, the constraints placed on a field measurement system are:

a. Equipment limited to a digital voltmeter
b. Semi-skilled, high school educated individuals will be performing the measurement

Based on these constraints and the difficulty of access to the electrical system, it is recommended that a highly reliable, well constructed panel be purchased for use and a simple visual inspection system be adopted. Experience at the Coast Guard Research and Development Center has shown that the condition of a panel can be rapidly appraised visually if the substrate of the panel is transparent. A transparent substrate allows the detection of corrosion and salt water intrusion that is not always possible with opaque substrates. In order to adopt a visual inspection system, the film laminate panel construction with a transparent substrate must be selected. With a minimal amount of training, maintenance personnel could be trained to inspect panels for corrosion, etc.

The consideration of field usage argues that a film laminate panel subject to the material constraints of section 8.2 be selected with a glass on glass construction which can easily be visually inspected.

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